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Biodiesel/Cummins CRADA Report

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16. Abstract (MAXIMUM 200 WORDS)

As an element in the Coast Guard's compliance strategy for decreasing greenhouse gases (GHG), and increasing the use of alternative fuels, the USCG Research & Development Center tested 100 percent biodiesel (B100), a renewable alternative diesel fuel, on a USCG 49' Buoy Utility Stern Loading (BUSL).

B100 derived from Waste Vegetable Oil (WVO) was obtained from a local supplier, and fuel quality was monitored throughout the test. Prior to operational testing, a materials audit for compatibility with B100 was performed on the fuel-wetted components on the three diesel engines (two main propulsion engines and one generator), and incompatible components were replaced with suitable substitutes. Break-in testing was conducted before the start of operational testing to ensure no B100 compatibility issues remained. Engine exhaust emissions were not measured, but were estimated though an analysis of previous studies on similar engines.

Operational testing was conducted over a one-year period starting in March 2013. During this time, the BUSL carried out typical missions in its normal eastern Long Island Sound operating area. Engine performance data were collected and analyzed, along with crew observations of boat performance and maintenance. Details of the testing, and the conclusions and recommendations are included in the report.

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biodiesel, B100, gelling, emissions, alternative fuel, greenhouse gas, GHG, BUSL Tier II testing, Energy Independence and Security Act (EISA), ORNL, Cummins, cloud point, , compatibility, waste vegetable oil (WVO)	Distribution Statement A: Approved for Public Release; distribution is unlimited.		
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EXECUTIVE SUMMARY

Federal mandates issued in recent years have focused additional attention towards reducing energy use and Greenhouse Gas (GHG) emissions, and increasing the use of renewable energy sources. Two prominent examples are the Energy Independence and Security Act (EISA) of 2007, which sets requirements for reducing energy and increasing the use of alternative fuels, and Executive Order (EO) 13514, which requires agencies to establish reduction targets for GHG. To meet these requirements, the United States Coast Guard (USCG) has commissioned studies, with an overarching objective of reducing its carbon footprint through various approaches.

As part of this effort, the USCG Research and Development Center (RDC) initiated studies to examine alternative fuels, leading to the current Operational Testing Project. The first study addressed Alternative Fuel Options for Coast Guard (CG) boats, identifying options for replacing the diesel currently used on boats. The study identified 100 percent biodiesel (B100) as an alternative to diesel. A second study developed plans to test these alternative fuels in CG boats, and assess boat modifications required to use the fuel. The third study (and current project) executed the test plans to quantify implementation issues, benefits and impacts of using the alternative fuel in CG boats under typical mission conditions (Operational Testing). This report addresses the results of the B100 testing.

Operational testing took place over a full year in order to experience all typical environmental conditions and operational activities at the unit. Testing took place on a 49’ Buoy Utility Stern Loading (BUSL) operating out of Aids to Navigation Team (ANT) Long Island Sound (LIS), located in New Haven, CT. Test data included environmental data, engine/fuel system data and crew observations. The RDC and Cummins, the original equipment manufacturer for the BUSL engines, entered into a Cooperative Research and Development Agreement (CRADA) to study the use of B100 in the BUSL. Cummins provided engineering support and helped identify and execute needed changes to the engines and fuel system to ensure B100 compatibility. In addition, Oak Ridge National Laboratory (ORNL) provided expertise relating to the fuel specification, B100 compatibility, and emissions. Analysis performed by ORNL suggests that emissions from biodiesel fueled engines pose two benefits. Biodiesel emissions contain lower levels of carbon monoxide (CO), hydrocarbon (HC) and particulate matter (PM) pollutants with slightly higher Nitrogen Oxides (NOx). In addition, because biodiesel contains carbon that has been derived from plant sources, its emissions represent a much smaller net contribution to atmospheric GHG levels.

Based on the testing in this study, B100 could be used as an alternative fuel for diesel boats on a case by case basis if the fuel gelling issues can be mitigated. In addition, a break-in period is required to (1) ensure all needed changes have been made to guarantee the materials compatibility with B100, and (2) allow time to correct any issues that might be caused by prior carbon deposits going into and back out of solution in other parts of the fuel system, such as filters. The most significant problem experienced was gelling of the B100, which clogged fuel filters and caused the main engines and generator to shut down while underway. Gelling occurs when the fuel temperature is lower than the cloud point (33.5°F for the test fuel). Gelling can be prevented through fuel management (e.g., fuel additives, shifting to a diesel/biodiesel blend), or through design (e.g., insulation, tank heaters).

Although not the intended focus of this project, testing showed that special attention must be given to ensure the proper production, transfer and storage of B100. Currently B100 is widely available, but not widely or uniformly distributed or produced, compared to diesel. Variations exist in B100 properties, quality and cost, as subsidies are phased in or out, and as suppliers produce B100 using different source fuels (feedstock). B100 should be sourced from a BQ-9000 certified producer and marketer to avoid fuel quality problems.

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LIST OF ACRONYMS

ACOE	Army Corps of Engineers
ANT	Aids to Navigation Team
ASTM	American Society for Testing and Materials
ATON	Aids to Navigation
B0	Diesel (0% biodiesel diesel)
B20	20% biodiesel
B70	70% biodiesel
B100	100% biodiesel
BUSL	Buoy Utility Stern Loading
CESE	Center for Environmental Science and Engineering
CG	Coast Guard
CNG	Compressed Natural Gas
CO	Carbon monoxide
CO2	Carbon dioxide
COG	Course over ground
CRADA	Cooperative Research and Development Agreement
CTR	Connecticut Tank Removal
DOE	Department of Energy
EISA	Energy Independence and Security Act
EO	Executive Order
EPA	Environmental Protection Agency
FAME	Fatty acid methyl ester
FEMP	Federal Energy Management Program
GHG	Greenhouse gas
GPS	Global Positioning System
HC	Hydrocarbon
HDRD	Hydrogenation-derived renewable diesel
HR	Hour
HP	Horsepower
Hz	Hertz
IMO	International Maritime Organization
KG	Kilogram
KT	Knot
KW	Kilowatt
LIS	Long Island Sound
MDE	Main diesel engine
MPH	Miles per hour
NEME	New England Marine Electronics
NM	Nautical miles
NMEA	National Marine Electronics Association
NOAA	National Oceanic and Atmospheric Administration
NOx	Mono-nitrogen oxides (NO and NO_2)
OD	Outside diameter
ORNL	Oak Ridge National Laboratory

LIST OF ACRONYMS (CONTINUED)

PM	Particulate matter
RDC	Research & Development Center
RPM	Revolutions per minute
STBD	Starboard
TCTO	Time Compliance Technical Order
UCONN	University of Connecticut
USCG	United States Coast Guard
VDC	Volts direct current
WSF	Washington State Ferries
WVO	Waste Vegetable Oil

1 BACKGROUND

In recent years, the International Maritime Organization (IMO), Environmental Protection Agency (EPA), the U.S. Congress, and the White House have established policies designed to reduce air pollutants, reduce carbon footprint and encourage the use of alternative fuels. Some of these actions, particularly in the federal domain, influenced initiation of this project and are described below.

1.1 Federal Mandates and Greenhouse Gas Emissions

The Energy Independence and Security Act (EISA) of 2007 (P.L. 110-140, H.R. 6) aims to increase U.S. energy security, increase the use of biofuels, and improve vehicle fuel economy. Using 2005 as a baseline, EISA requires federal agencies to reduce facility energy consumption by 30 percent, reduce petroleum consumption by 20 percent, and increase alternative fuel consumption by 10 percent by 2015.

Executive Order (EO) 13514; Federal Leadership in Environmental, Energy, and Economic Performance (2009), requires agency-wide reduction targets and reduction goals for energy, water and waste. E.O. 13514 also requires agencies to establish reduction targets for direct greenhouse gas (GHG) emissions from sources that are owned or controlled by the Federal agency, defined as Scope 1 emissions. An example of Scope 1 emissions are those from United States Coast Guard (USCG) boats. To support these goals, the Coast Guard (CG) has commissioned studies designed to research and test alternate fuels with an eye towards greater accountability of fleet fuel usage, reduced greenhouse emissions and future cost savings.

1.2 Alternative Fuels

Alternative fuels are fuels other than traditional petroleum based gasoline or diesel. Replacing traditional fuels with biofuels can reduce the carbon footprint. Biodiesel is an alternative fuel that is the subject of this report, and is a clean burning, renewable fuel produced from a wide range of feedstock consisting of vegetable oils, animal fats and waste vegetable oil (WVO). B20 (20 percent biodiesel blended with 80 percent diesel) is permitted by most major engine manufacturers for use in current production diesel engines with no modifications. Use of higher blends might be possible with minor modifications, depending on the engine and fuel system. Engines running on biofuels emit carbon dioxide (CO_2), the primary source of greenhouse gas emissions. However, because plants and trees are the raw material for biofuels (or their source oils), and because they need carbon dioxide to grow, the use of biofuels does not add CO_2 to the atmosphere, but recycles existing atmospheric CO_2. The use of fossil fuels on the other hand, releases carbon that has been stored underground, generating a net CO_2addition to the atmosphere. Biofuels are not carbon neutral however, as they still require fossil fuels such as coal and natural gas for their production. The Coast Guard Research and Development Center (RDC) initiated several studies to examine alternative fuels, with two of the studies leading to the current Operational Testing Project. These studies are described below.

2 OVERVIEW OF THE OPERATIONAL TESTING PROJECT

The Operational Testing Project is the third in a series of RDC studies that examined the use of alternative fuels to potentially substitute for E10 gasoline and diesel. This report presents the results of testing on the diesel alternative: Fatty Acid Methyl Ester (FAME) biodiesel.

2.1 Project 1: Alternative Fuel Study

The first RDC study addressed Alternative Fuel Options for USCG Vessels, identifying alternative fuels, appropriate boat classes, and locations for testing. Eight diesel alternatives were evaluated against 25 attributes that represented measures relating to affordability, availability, safety, and potential carbon footprint reductions. Three alternative fuels emerged from this analysis as the best candidates for testing: Fatty Acid Methyl Ester (FAME) biodiesel, Hydrogenation-derived Renewable Diesel (HDRD), and compressed natural gas (CNG).

2.1.1 Test Fuel

The RDC and sponsor selected 100 percent biodiesel (B100) for the diesel fuel demonstration. HDRD was eliminated on the basis of cost and availability. CNG was eliminated due to low volumetric energy density, the problems associated with siting fuel tanks, the costly and extensive modifications required to the fuel system and the engine, along with the perceived risk with high pressure fuel. Biodiesel was considered low risk, because it is reasonably priced compared to petroleum diesel, is defined under an existing ASTM specification, used successfully by others in marine applications, and is readily available from local certified sources. In addition, biodiesel has a lower toxicity and biodegrades more quickly than diesel, which is a significant advantage for use near or on the water. This can be a drawback in that water contamination in the fuel can foster microbial contamination. As with regular diesel, biocide additives can be used to minimize this issue, although none were used during testing. B100 was also expected to be used as a near drop-in replacement fuel with minimal modifications to the engine and fuel systems on the test boat - some boat preparations were anticipated, such as cleaning the fuel tanks and ensuring materials compatibility. Biodiesel is produced commercially from a variety of oils and fats. The Biodiesel in this test was made from recycled greases (used cooking and frying oils).

2.1.2 Test Platform and Location

The RDC selected the 49’ Buoy Utility Stern Loading (BUSL) as the test platform for the demonstration (Figure 1). Table 1 shows the BUSL characteristics. BUSLs are assigned to CG Aids to Navigation Teams (ANTs) to provide transportation and servicing capabilities in support of Short Range Aids to Navigation (ATON). The RDC selected ANT Long Island Sound (LIS) in New Haven, CT as the host unit for the testing, in part because two BUSLs are assigned there, making it easier to dedicate one for B100 use. The BUSLs at ANT LIS also have relatively high annual operating hours, which is a benefit to testing. With the test site located in the Northeast United States, the RDC expected to encounter a wide range of environmental conditions over the test period. ANT LIS assigned BUSL 49410 as the test boat. As the BUSL has Cummins main diesel engines (MDEs) and a Cummins generator, the RDC signed a Cooperative Research and Development Agreement (CRADA) with Cummins to provide technical assistance and engineering support during the testing. Cummins provided technical input for the fuel selection and test plan, recommendations for other system modifications including filters, and replacement components for B100 incompatible engine and fuel parts.

Figure 1. BUSL.

Table 1. BUSL characteristics.

Operational Characteristics		Physical Characteristics	
Range	400 NM @ 10 knots	LOA	49’-2 ¼”
Max Speed	10.5 knots @ 2300 RPM	Beam (Maximum)	16’-10”
Cruise Speed	7 knots	Draft (Full Load)	5’-4”
Max Range	400 NM @ 10 knots	Propulsion	Two, Cummins, 6CTA8.3 M1, 305 horsepower each @2300 RPM
Fuel Consumption	100 gallons/trip 600 gallons/month	Generator	20 kW, Single Phase, 60 Hz, 120 volts alternating current @ 1800 RPM
		Generator Engine	Cummings ONAN 4B3.9 21 kW
		Fuel Tank Capacity	783 gallons @ 95%
		Number of Fuel Tanks	2
		Crew	Four crew, three passengers
		Deckhouse	Aluminum
		Hull	A-36 Steel

2.1.3 Oak Ridge National Laboratory

The RDC established an interagency agreement with the Department of Energy (DOE) to obtain technical support from the Oak Ridge National Laboratory (ORNL) for the biodiesel testing. ORNL provided:

- guidance to RDC and Cummins on the fuel issues;
- input and review of a protocol to assure fuel quality and compatibility during the tests;
- an emissions analysis based on a literature review (the RDC decided that direct measurement of emissions was not practical nor cost effective)

2.2 Project 2: Test Plan Development

A second RDC study was conducted to develop a Biodiesel Test Plan (Appendix C). In addition, a draft Time Compliance Change Order (TCTO) (5Appendix A) was prepared, describing planned changes to the BUSL engines and fuel system to prepare for testing. The changes that were implemented are discussed in Section 2.3.1. The protocol developed for testing alternative fuels included four phases: materials, bench, field, and operational testing, with materials and bench testing amended as noted below for the diesel alternative.

- **Materials Testing** is typically conducted to determine the compatibility of fuel-wetted parts with B100. Due to the vast amount of previous studies on biodiesel use, compatibility was determined by a materials audit, based on Cummins' expertise, and information derived from published materials test results.
- **Bench Testing** is typically conducted on a diesel engine in a stationary test cell environment where engine operating parameters, such as fuel consumption, performance, and emissions, are monitored under controlled conditions. Because biodiesel is in current use and its performance is well documented, no B100 bench testing was required for the BUSL engines.
- **Field Testing** was conducted on the BUSL under controlled operating conditions, to develop baseline data, and to diagnose and correct problems prior to operational testing.
- **Operational Testing** was conducted on the BUSL over a 12-month period to assess the feasibility of using B100 in CG boats during normal operations.

2.3 Project 3: Operational Testing

The current RDC study carried the investigation of alternative fuels forward to the next phase, executing the test plan developed in the previous study. The objective of this phase was to identify and quantify any implementation issues, benefits and impacts of using B100. Testing focused on operations, engine performance, engine maintenance, crew health and safety, and the environment, with the goal of experiencing "no impacts that would be considered worse than the status quo" in these primary areas. In the long-term, the purpose of operational testing was to contribute to the CG's overall goal of achieving the carbon reduction mandate described earlier, by converting a portion of its boat fleet to a renewable fuel.

2.3.1 Test Preparations

This section describes actions that were completed to prepare the BUSL for testing, and to establish other needed support.

2.3.1.1 Materials Compatibility and Fuel System Cleanliness

One of the primary concerns with biodiesel is its solvent action and compatibility with materials used in engine and fuel system components. Many diesel fuel systems do not use B100 compatible materials, since the engines were not designed for that fuel. This section describes the potential impact of incompatibility and the efforts taken to ensure that fuel wetted materials and parts in the BUSL engines and fuel systems were ready for testing with B100.

- B100 is an excellent solvent, and can loosen or dissolve varnish and sediments in fuel tanks and fuel systems left by diesel over time. The BUSL fuel tanks and fuel system were cleaned before using B100. There were no shore-side storage tanks involved, as the fuel was delivered directly into the BUSL, from the delivery truck in a "just in time" method.
- B100 can soften certain types of rubber compounds (buna-N, nitrile rubber, natural rubber) that are commonly used for hoses, seals and gaskets, and may degrade them to the point where they fail. Failure can lead to spilled fuel on a hot engine, can ruin a fuel pump, or clog a filter.
- B100 is not compatible with some metals and plastics. Biodiesel will degrade and form high sediment levels if in contact with copper or copper containing metals (brass, bronze), or with lead, tin, or zinc (galvanized surfaces) for long periods. These high sediment levels may clog filters.
- B100 may also permeate some common plastics (polyethylene, polypropylene) over time, so these should not be used in fuel storage and transfer systems.

BUSL Fuel System.
The RDC audited BUSL fuel system compatibility by comparing the materials and parts in the BUSL fuel system, with the incompatible metallic and non-metallic materials listed in Appendix E of the Biodiesel Handling and Use Guide, Fourth Edition (NREL/TP-540-43672 Revised December 2009). The fuel-wetted components were identified using the BUSL fuel system arrangement drawing and materials list (Berry, 1997) and the BUSL fuel tank cleaning specification (USCG SFLC, 2011). For components that did not have the materials listed, the test team contacted equipment manufacturers to determine compatibility. The test team contracted Connecticut Tank Removal (CTR), to clean and strip the BUSL fuel tanks after removing the diesel. The test team also had planned to swap out the installed Racor 500 filter with a bio-compatible replacement that included a heater option (Racor 777 filter assembly). However, on the recommendation of the original suppliers of the BUSL engines (Cummins Marine of Glen Burnie, MD), the RDC instead opted to install an RCI fuel purifier fitted with a 24V heater on the inlet side of the fuel system (Figure 2). The advantage of the RCI purifier is that it combines a water separator, a fuel coalescer and a heating element in one product. The heating feature factored into cold weather planning as described later in this report. The original Racor filter remained in the system based on Racor's feedback that it was biodiesel compatible.

Figure 2. RCI fuel purifier installed on starboard Racor mount.

Cummins Engine Fuel Systems.
Cummins reviewed the BUSL MDEs and generator and provided replacements for incompatible parts. The fuel pump components and the fuel injectors in the engines (Bosch model MW on the C8.3 main engines, and Bosch P7100 on the B3.9 generator engine) had no identified material compatibility issues with B100, and the fuel supply tubes were also determined to be compatible. Required changes were limited to the replacement of some washers and gaskets, and all fuel supply hoses. Certified Cummins technicians from Cummins Power of Rocky Hill, CT installed the parts. Cummins reviewed the BUSL engines and did not recommend any major engine adjustments to burn B100, such as an engine teardown or a change in the injector timing. Table 2 summarizes the list of parts that were changed. This list was provided as part of a Field Testing Replacement Parts Guide developed by Cummins for this project. This guide is provided in 5Appendix D.

Table 2. Cummins-provided replacement parts.

Part No.	Description	Material	Option used on	Quantity Per Engine	Replacement Part
Main Propulsion					
3918190	Washer, Sealing	Rubber coated steel	FX9008 – Injection Pump Supply	2	3684342
3903380	Seal, Banjo Connector	55002 – 99% Copper	FT9873-04 – Fuel Plumbing	6	3069182
3918188	Washer, Sealing	Rubber coated steel	FT9873-04 – Fuel Plumbing	2	3069182
3918192	Washer, Sealing	Rubber coated steel	FT9873-04 – Fuel Plumbing	2	3963988
3918191	Washer, Sealing	Rubber coated steel	FS9006-03 Fuel System Accessories	2	3963990
Generator					
3903380	Seal, Banjo Connector	Copper (99% min)	FT9901-02 – Fuel Plumbing	6	3069182
3918188	Washer, Sealing	Rubber coated steel	FT9901-02 – Fuel Plumbing	2	3069182
3918191	Washer, Sealing	Rubber coated steel	FS9088 – Fuel System Accessories	2	3963990
3918192	Washer, Sealing	Rubber coated steel	FF9741-04 – Fuel Filter Plumbing	2	3963988
3918191	Washer, Sealing	Rubber coated steel	FF9028-03 – Fuel Filter	2	3963990
3923083	Hose, Flexible	¼" rubber tube, single	FP97333 – Bosch Injection Pump	1	3923083M[1]

[1]The part provided to replace the flexible hose (last row) was not installed because the hose was not part of the generator fuel pump configuration on the BUSL.

2.3.1.2 *Data Collection*

New England Marine Electronics (NEME) was contracted to install most of the data collection system. The following components were installed to create an NMEA 2000 network connected to a data-recording computer located in the pilothouse.

- Chetco SeaPC. This is a Windows-based computer made for a marine environment. It can run on 12-24 V DC and has a solid state hard drive to better withstand vibration and impacts. Chetco vDash™ software was used to monitor and record the NMEA 2000 data. The computer was connected to a hot spot installed on the BUSL bridge. A hot spot is a wireless router that connects the computer (via BlueTooth) with a remote site (via the cellular network). This setup allowed the test team to monitor the network remotely.
- Airmar. An Airmar 200WX weather station with Global Positioning System (GPS) was installed on the top of the bridge to collect GPS position, direction, speed over ground, course over ground (COG)najut, air temperature and humidity.

- Maretron. Older diesel engines, like those on the BUSL are completely analog, i.e., without a digital interface. NEME installed the following components to convert the analog data and digital fuel data to the NMEA 2000 protocol.
  - Maretron EMS100 Engine Monitoring System Computer
  - Maretron FFM100 Fuel Flow Meters Control Unit
  - Maretron FFM100 Fuel Monitoring System
  - Maretron M2RSP-2-E8 Fuel Flow Meters (2 EA)
  - NMEA 2000 network (powered by 12VDC)
- Two fuel flow meters were installed to compute the amount of fuel burned. This was needed because the Cummins engines return about 70% of the fuel they pump for cooling and lubrication. With one fuel meter installed on the inlet side of the engine, and the other on the return side, the control module reports the difference, which equates to the fuel burned. It also provides the fuel temperature.

The resulting NMEA networked system is shown in Figure 3.

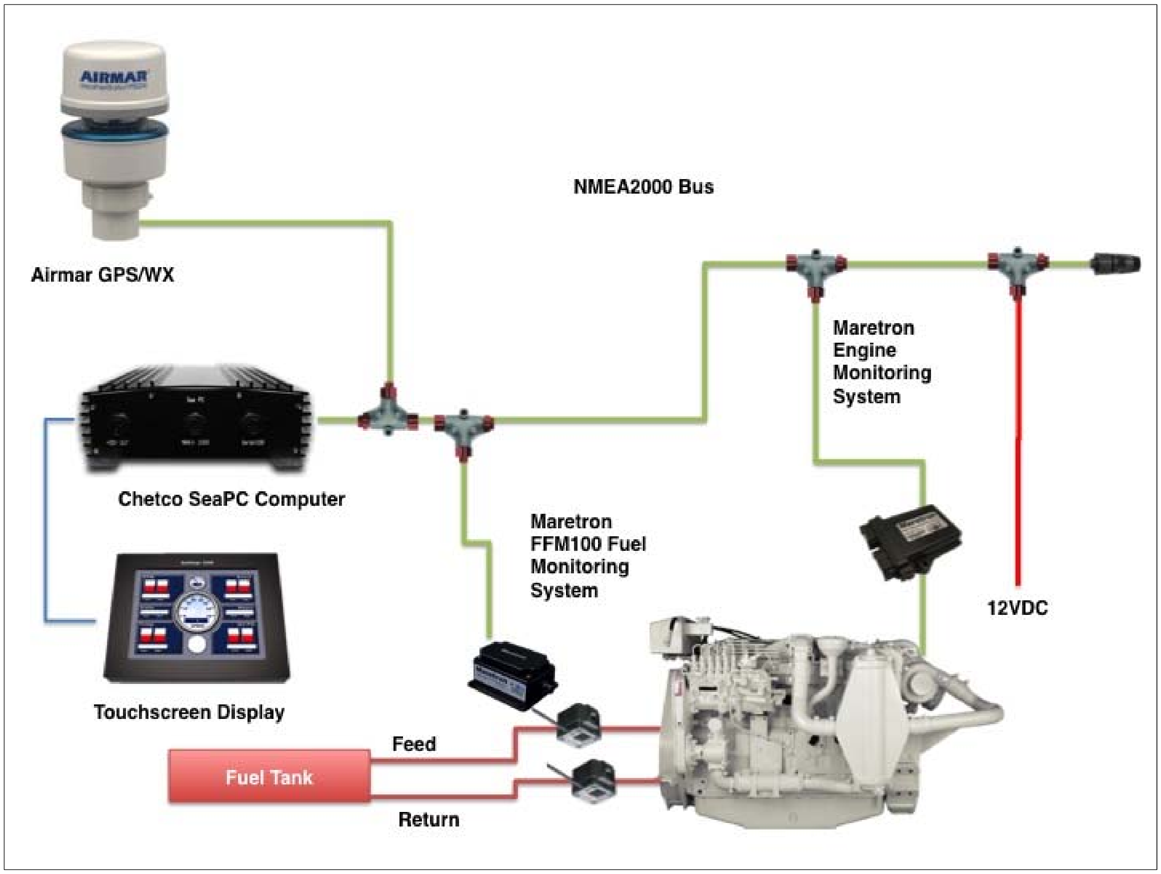

Figure 3. NMEA 2000 network system.

2.3.1.3 Shaft Instrumentation

In addition to the data collection system described above, "ShaftMaster" shaft instrumentation was installed by Hillhouse Industries. While the ShaftMaster product might be an excellent tool for larger shaft applications, it appeared not to work well for the 2 ¾" shaft on the BUSL. The data appeared to be accurate for short periods, and then appeared to lose calibration due to sensor misalignment. Despite a significant

effort to install and repair the system, the data collected was deemed not reliable, e.g., data sometimes indicated over 1000 horsepower (HP) output, although the BUSL engines are rated for 305 peak HP. The combined, planned data output from the shaft instrumentation and the NMEA network, once fully configured, is shown in Table 3.

Table 3. B100 monitored parameters.

Subsystem	Parameter	Source of Data
Boat Dynamics	BUSL Position	GPS/WX Station
	Speed over Ground	GPS/WX Station
	Course over Ground	GPS/WX Station
	Air Temperature	GPS/WX Station
	Wind Speed	GPS/WX Station
	Atmospheric Pressure	GPS/WX Station
	Humidity	GPS/WX Station
	Heading, Pitch, Roll	GPS/WX Station
Engine Dynamics	Fuel Flow (feed and return)	Maretron
	Fuel Temperature	Maretron
	Shaft RPM, torque, and horsepower	ShaftMaster
	Engine RPM	Maretron
	Engine Hours	From USCG
	Engine Temp	Maretron
	Oil Pressure	Maretron

2.3.1.4 Crew Interviews

In addition to the quantitative data described above, data included observations from the BUSL crew, gained from informal interviews during visits to the BUSL. To assist in obtaining the most useful crew data, the test team provided training prior to the start of testing, including the following topics:

- Project background and goals of testing
- Overview of biodiesel fuel: production, advantages, disadvantages
- Differences between diesel fuel and biodiesel
- Safety and health-related issues
- Changes in maintenance procedures
- Changes in Federal and state regulations with respect to spill reporting, etc.
- Changes in fuel logistics
- Use and monitoring of data acquisition system

2.3.1.5 B100 Fuel Supply and Analysis

Biodiesel One of Southington, CT was selected to provide B100, produced from WVO for the test. Fuel delivery was set up to pump directly into the BUSL fuel tanks from the fuel delivery truck (no B100 storage tanks were used at ANT LIS). In addition to supplying the fuel, the contract also required laboratory testing for each batch of fuel produced, to monitor fuel quality using selected tests from the ASTM B100 fuel standard D6751. BiodieselOne arranged for the University of Connecticut's (UCONN) Center for Environmental Science and Engineering (CESE), as well as Gorge Analytical, to meet this testing requirement. The eight tests included, and the reference standard for each are listed in Table 4.

Table 4. BiodieselOne fuel analysis tests.

Test Name	Test Standard
Cloud Point	ASTM Method D2500
Cold Soak Filtration	ASTM Method D7501
Free & Total Glycerin	ASTM Method D6584
Oxidation Stability	EN Method 14112
Total Acid Number	ASTM Method D644
Water & Sediment	ASTM Method D2709
Sulfur	ASTM Method D4294 or D5453
Flash Point	ASTM Method D93

In addition, the RDC developed a fuel analysis plan to monitor fuel quality An solicitation using a RFQ resulted in the UCONN laboratory being selected. In most cases, samples of the incoming fuel were collected during deliveries; however some samples were taken from the BUSL fuel tanks. The RDC test program included 14 parameters as indicated below (Table 5). Two additional tests were performed on the incoming fuel immediately upon delivery: the "clear and bright" test and the pHlip test.

Table 5. RDC fuel analysis tests.

Test Name	Test Standard
Cloud Point	ASTM Method D2500
Cold Soak Filtration	ASTM Method D7501
Free & Total Glycerin	ASTM Method D6584
Oxidation Stability	EN Method 14112
Total Acid Number	ASTM Method D644
Water & Sediment	ASTM Method D2709
Sulfur	ASTM Method D4294 or D5453
Flash Point	ASTM Method D93
Biodiesel % Content	ASTM Method D7371
Kinematic Viscosity	ASTM Method D445
Copper Strip Corrosion	ASTM Method D130
Phosphorous	ASTM Method D4951
Calcium & Magnesium	EN Method 14538
Sodium & Potassium	EN Method 14538
Distillation, T90	ASTM Method D1160
Carbon Residue	ASTM Method D4530
Sulfated Ash	ASTM Method D874
Methanol Content	EN Method 14110

2.3.1.6 Cold Weather Planning

B100 gels and thickens at a higher temperature than most diesel fuel. B100 has a temperature specific characteristic called a cloud point, which is a function of the production process, and influenced by the feedstock used. Most B100 starts to cloud between 35 to 60°F so a means to control the fuel temperature may be needed even in moderate climates. When B100 drops below the cloud point, it becomes cloudy and begins to gel (creates a waxy substance), increasing viscosity to much higher levels than most diesel fuel. This can increase the stress on pumps, clog fuel system components like filters, and eventually cause the

engines to shut down. The gelling effect reverses as the B100 temperature increases, however the process may take up to an hour for the warmed fuel to return to a more normal, fluid state.

The fuel specification required a minimum cloud point of 33.5°F, however it was not known how cold the fuel in the BUSL tanks would become under very cold environmental conditions. Considering a potential gelling issue, the test team weighed various options, and decided to operate with B100 in the cold months so that problems could be experienced and documented, instead of switching to diesel or a diesel/biodiesel blend. The test team also concluded there was a high probability that the factors listed below would prevent the fuel temperature from falling below the cloud point:

- Although the local average daily low air temperatures from December through March may go below 32°F, the average water temperature is about 35°F, and the side and bottom of the BUSL fuel tanks are exposed to the water.
- The remaining sides of the tanks are exposed to the ambient temperature in the engine room, which is kept well above the cloud point (near 70 F).
- Fuel in the fuel lines would be above cloud point so the engines would have warm fuel to get started and the warm return fuel would enter the bottom of the fuel tank and help warm the fuel in the tank (because the fuel is also used as a lubricant, additional fuel is circulated; only about 30 percent is burned, and the rest is returned to the tank).
- An RCI fuel purifier fitted with a 24V heater was installed on the inlet side of the fuel system, with the intention of providing heat to the fuel prior to going to the engine.
- Maretron fuel flow meters indicated the fuel temperature passing through the fuel line, allowing the test team to monitor the fuel temperature.

2.3.1.7 Additives

An antioxidant was used to enhance the long term storage characteristics of the B100 fuel and as a means of meeting the three hour oxidation test standard. An anti-gelling additive was also used (see Section 3.2.3for details). A biocide additive can be used to prevent microbial growth, as biodiesel can experience microbial contamination if water is present in the fuel. No microbial contamination was experienced during the test period, and a biocide was not needed. This may have resulted from the rapid turnover of the fuel for much of the test period, and the cleanliness of the fuel tanks and fuel (fuel analyses showed water-free fuel upon delivery).

2.3.1.8 Test Preparation Costs

The costs for preparing the BUSL for operational testing are provided in Table 6. These costs include parts and contract labor for ensuring B100 compatibility, and installing instrumentation for data acquisition. Labor costs by ANT LIS and the test team are not included.

Table 6. B100 test preparation costs.

Item	Cost
NMEA 2000 Engine monitoring network	$7,865
Labor for Cummins parts swap	$1,165
RCI Heated fuel purifiers	$1,784
ShaftMaster shaft monitoring system	$9,500
Chetco SeaPC data recorder	$3,250
Viton manhole gaskets	$1,147
AllB100 compatible Racor Filter assembly	$2,250
B100 compatible fuel hoses	$851
Airmar GPS/WX station	$1,150
Tank cleaning (includes B0 fuel removal)	$4,780
Total	**$33,742**

3 OPERATIONAL TESTING

Operational testing began on 11 March 2013, after engine and fuel system modifications were completed and shaft instrumentation and the data collection system were installed. Testing concluded on 17 March 2014, after 412 underway hours, 5,500 gallons of B100, and 233 gallons of diesel were used. The BUSL switched to a 70 percent biodiesel blend (B70) on 15 January 2014, and on 4 February 2014 switched back to 100% diesel to complete the remainder of the testing. The B70 was an ad hoc blend that was used to address a fuel gelling issue, described in Section 3.2.3. The average sortie was 6 hours, burning 70 gallons of B100. Weather conditions varied over a wide range and extremes are noted in the below table.

Table 7. Weather extremes during operational testing.

Measure	High	Low
Air temperature ºF	96	13
Water temperature ºF	58	29.5
Humidity %	100	20

3.1 Test Procedures

3.1.1 Field Testing

Field Testing (also referred to as baseline testing) began in January of 2013 and included idling at the pier, and underway at clutch-in, cruising, and full speeds. As the testing progressed, the test team recognized that under normal operations, the BUSL was typically either idling while performing buoy work, or wide open throttle (approximately 11 kts) transiting to the next work location. Baseline testing was therefore changed to match this operating profile/duty cycle. On 4 February 2013, the diesel fuel remaining in the tanks was pumped out, and the tanks were stripped and cleaned (Figure 4). B100 was loaded into the tanks on 5 February 2013 and B100 baseline testing began that same day. After the first run of B100 baseline testing was completed, a second planned test run was delayed when operating hour restrictions were placed on the BUSL as a result of federal budget issues. Once the restrictions were lifted, the second B100 baseline run was cancelled due to the positive results obtained in the first run, and operational testing began.

Figure 4. Stripped starboard fuel tank and pickup pipe.

3.1.2 Operational Testing

Operational testing began on 11 March 2013. During this testing phase, the BUSL performed typical duties, such as responding to ATON outages and performing regular scheduled ATON maintenance. Operating data were monitored and collected from the instrumentation.

3.1.3 Bollard Pull Testing

A “bollard pull” is a test conducted by running the MDEs at full throttle with the BUSL tied to the dock (to the bollards). Bollard pulls were not considered when the test plan was written. Based on the configuration and good condition of the ANT LIS dock, bollard pulls appeared to offer a way to run baseline tests under tightly controlled conditions, allowing for comparisons over the one-year test period, not only with B100, but with diesel as well. In addition, bollard pulls were viewed as a potential workaround, to continue some testing while budget restrictions prevented operating underway. The test team made several bollard pull attempts. In each case, the test was secured when high temperature alarms sounded on the MDEs. The test team and the engineers at ANT LIS concluded that the BUSL hull was too close to the bottom, and the propeller wash stirred up sediment affecting the heat exchangers (the BUSL engines are cooled by keel coolers). No further attempts were made to conduct bollard pulls.

3.2 Testing Outcome

Testing in this study demonstrated that after a break-in period, the BUSL could perform all of its missions using either B100 if the fuel gelling issues are addressed. The break-in period has two purposes. First, a series of actions is required to ensure that the BUSL is compatible with the fuel. An incompatible part that is not identified or not replaced will eventually produce a fuel leak. Second, carbon deposits produced by the previous use of petroleum diesel may be dissolved and later deposited downstream in the fuel system, causing problems. The break-in period provides an opportunity for heightened vigilance, e.g., more frequent checks for leaks, additional fuel filter inspections, etc., to detect such issues. Some issues arose during testing, in particular gelling of B100 in cold weather, and the crew noticed some differences in the operating characteristics of the engine. Specific outcomes are described below.

3.2.1 Fuel Effect on Boat Performance

Differences in engine performance that resulted from the switch from the baseline petroleum diesel fuel (B0) to B100 were examined from continuous measurements of engine RPM, temperature and fuel consumption for the starboard MDE. Measurements were collected and stored on a daily basis. Each daily file contained measurements for both idle periods and full throttle periods, the two predominant BUSL operating conditions, where the BUSL would move at idle speed from the harbor, go to full speed in transit to each work site, idle on station, and so on. The daily files represent engine performance during four scenarios: B0 idle, B0 full throttle, B100 idle, and B100 full throttle.

Data were extracted from the daily files that included reasonably long and consistent periods of operation for each of the four scenarios. The extracted scenario data were filtered with a 3σ filter to remove data outliers and were then combined into four ensembles representing each of the scenarios. Averages and standard deviations of each of the engine parameters were calculated for each ensemble. Table 5 presents the summary statistics generated for each of the four engine speed and fuel ensembles.

- The ensemble average (average of all daily data file extracts) for each ensemble was calculated from the individual daily data set statistics as:

$$Ensemble\ Average = \frac{\sum_{i=1}^{N} M_i \mu_i}{\sum_{i=1}^{N} M_i}$$

where

N = number of data sets
M_i = the number of data points in data set i
μ_i = the average of data set i

- The ensemble-standard deviation (square root of variance) was calculated from the individual daily data set statistics as:

$$Standard\ Deviation = \sqrt{E[x^2] - E[\mu_i]^2}$$

where

$E[x^2]$ is the mean of x^2, calculated as the ensemble average from the combined daily extract averages of x^2
$E[\mu_i]^2$ is the square of the average of the daily data file extract averages μ_i

Table 8. Performance summary statistics.

Idle Speed							
Fuel	Total data points	Average			Standard Deviation		
		RPM	GPH	Temp (°F)	RPM	GPH[1]	Temp (°F)
B0	108,164	725	0.14	166.6	90.7	0.9	7.8
B100	319,447	665	0.3	167.2	147.9	0.6	4.7
% difference		-8%	139%[1]	0%			
[1]Fuel consumption at idle speed is so low that this large percentage difference is probably not an accurate or relevant metric.							
Full Throttle							
Fuel	Total data points	Average			Standard Deviation		
		RPM	GPH	Temp (°F)	RPM	GPH	Temp (°F)
B0	74,394	2295	10.3	176.7	17.9	0.3	2.3
B100	224,818	2291	11.3	176.2	33.2	1.5	2.6
% difference		0%	+10%	0%			

Performance summary statistics indicate:

- Engine idle speed is 8 percent lower with B100. This observation is attributed to the lower volumetric energy density of B100. B100 made from the most common feed stocks has about 8 percent less energy content per gallon than typical B0 (National Renewable Energy Laboratory 2009).
- At full throttle (11 mph), the engine runs at the same RPM with both fuels. This reflects the control by of the engine governor, which orders the same RPM for both fuels at full throttle.
- Fuel consumption at full throttle is 10 percent higher with B100. This also reflects the lower energy density of B100.
- Engine operating temperatures at idle and full throttle speeds were equivalent for the two fuels.

3.2.2 Fuel Effect on Engine Maintenance and Service Life

This testing demonstrated that once the engine systems and fuel systems are modified to use B100, and a break-in period was completed, the fuel selection had no significant impact on the workload of the boat crew or ANT engineers, on regular scheduled maintenance of the engine components or fuel system components, with the exception of gelling, described in Section 3.2.3. As long as the fuel remained above the cloud point and met the applicable specifications, the use of B100 would not impact the day-to-day operations and maintenance of diesel engines and their associated fuel systems. Long term effects on the engine and expected service life of the engine using B100 are not known; however, based on this test, there were no indications that B100 use would reduce engine service life. The lube oil on the BUSL was tested every operating day using the falling ball viscosity test. No abnormal viscosity results or indications of fuel dilution were observed by the crew during the operational testing period.

As a potential indicator of the effect on maintenance, the test team took photos of the injectors from the starboard MDE at the end of testing. No maintenance had been performed on them during operational testing. The test team determined the injectors showed normal wear and carbon deposits. A representative photo is shown below.

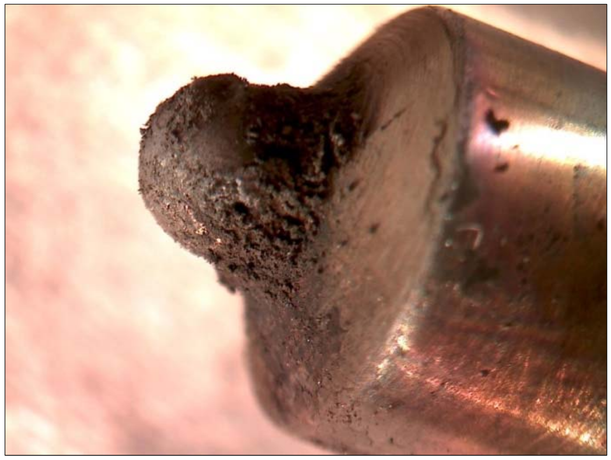

Figure 5. Representative fuel injector after testing

Some studies suggest two long term benefits on engines of biodiesel, compared to diesel. First, the cleansing effect of biodiesel, which can lead to problems during the break-in period, may have a positive long term impact, as parties having used significant quantities of B100 state that the engines upon inspection are cleaner internally and in fact seem to perform better (Zappi et al. 2003). Secondly, biodiesel has a higher lubricity which is a positive characteristic in terms of extending engine life, and has been reported to extend the useful life of moving parts with diesel engines:

> Biodiesel's superior lubricating properties can reduce wear in diesel engines. Bench scale tests have shown that 1% biodiesel can improve the lubricity of diesel fuel by as much as 65%. The lubricity of biodiesel will become increasingly important because EPA regulations will require the use of ultra-low sulfur diesel fuels in all U.S. highway diesel engines by 2006. Unfortunately, ultra-low sulfur diesel fuels can have poor lubricating properties. Low levels of biodiesel used as a lubricity additive can help solve this problem.[1]

Notwithstanding the above conclusion, some cautions are in order. As noted earlier in this report, biodiesel has a cleansing effect that may cause old deposits to dissolve and/or be dislodged, and travel in the fuel path to be deposited elsewhere in the fuel system. A heightened level of vigilance should be maintained during a break-in period, for example an additional maintenance procedure to open and inspect filters and sensors in the fuel system periodically. Second, despite best efforts to audit and replace all necessary incompatible parts, incompatible materials may remain undiscovered in an engine system, either because they are overlooked, or because component manufacturers cannot always identify every incompatible part. As a result, some anomalies during a break-in period may be anticipated. This caution comes from two incidents experienced during testing.

- High vacuum on a B100 fuel line during the first week of baseline testing caused an alarm condition and engine shutdown. The test team determined that the likely cause was a previous deposit that resulted in heavy residual diesel carbon/sediment on the Racor turbine, coalescing centrifuge, check ball, and rubber seal pieces. The fuel flow sensor was opened, and a small obstruction was discovered that was jamming the gears inside, which stopped the fuel from flowing to the engine.

[1] U.S. Department of Energy (2005)

- During a local buoy run, the generator shut down due to lack of fuel flow, and the STBD MDE shut down due to leaking air at the fuel filter selector valve. The boat engineer noticed bubbles rising from the bottom of the fuel bowl through the bottom drain plug, and suspected that the Racor filter drain plug was leaking air into the filter housing. Upon disassembly of the Racor fuel bowl, the O-ring disintegrated, leaving a black jellied mess in the engineer's hand. After discussions with Racor engineers, the complete fuel filter assembly was replaced due to incompatibility of the rubber components with B100. Initially, the test team intended to replace the Racor 500 filter with a B100 compatible model (Racor 777 filter assembly), but chose not to, based on Racor's feedback that the Model 500 was biodiesel compatible. The discovery of the problems described above, reinforce the need to include a break-in period when implementing a change from regular diesel to biodiesel.

3.2.3 Fuel Gelling

While the BUSL was underway on 19 December 2013, both propulsion engines stalled. The crew attempted to restart the engines, and observed vacuum gauges on the Racor assembly to read 23"Hg (normal operating readings are about 1 - 4"Hg.). The crew changed the filters and returned to base to troubleshoot. Engineers again noted excessive Racor filter vacuum and shifted filters. The engineer shut down the engines and changed all fuel filters to remedy the situation. Waxing (glycerin particles) was visible in the fuel bowl and on the filter elements. Temperature readings were taken in the engine room with a handheld Fluke temperature probe (Fluke 63-laser type), and the reading at the bottom of the tank/hull was equal to the specified cloud point (33.5°F). As reported by www.wunderground.com (2013), the daily low air temperature was 28°F in New Haven, CT on 19 December 2013. The test team concluded that the B100 cloud point was reached, and the wax within the fuel coagulated and produced deposits that collected in the filters, and significantly restricted the fuel flow. A fuel sample was taken for analysis that later indicated the B100 to be within specification. Figure 6 and Figure 7 illustrate the gelling that occurred on 13 December 2013.

On 20 December 2013, the test team used an anti-gelling fuel additive (FPPF biodiesel winter fuel treatment[2]) at the rate of one quart per 250 gallons of B100 fuel in each fuel tank to prevent further occurrence of gelling. While adding the FPPF seemed to help resolve the gelling, the process of reversing gelling is not well known, and the FPPF producer states that once the gelling process is started, it is difficult to reverse.

Figure 6. B100 completely separated in the oil-water separator.

[2] FPPF Bio-Diesel Winter treatment functions to prevent wax platelets from sticking together and keeps fuel flowing down to -40°F. It should be added to the fuel when the fuel temperature is around +40°.

Figure 7. B100 gel on a Racor filter.

Temperatures were recorded during subsequent visits. Table 9 shows the temperatures taken on the BUSL, as well as the sea temperature from a nearby NOAA reporting station. Note that on 9 January 2014, the reading at the bottom of the fuel tank was below the specified cloud point (33.5°F). Fuel gelling problems were experienced when NOAA water temperature dropped below 37°F (local measurements were 2°F to 4°F colder than the NOAA data.

Table 9. BUSL temperature data.

BUSL Fuel Temps Taken (2014)	9 Jan	23 Jan	29 Jan	6 Feb	13 Feb	28 Feb
Water temp reported by NOAA[1]	34°	34°	32°	32°	33°	34°
Actual water temp near side of BUSL	29°	30°	32°	33°	32°	36°
Hull temp outside near waterline	32°	32°	32°	33°	32°	37°
Temp probe in first inch of fuel	37°	39°	40°	38°	38°	39°
Temp probe bottom of tank in fuel	32°	32°	33°	33°	33°	33°

[1]NOAA sensor was located 1400 yards at 335° true from the BUSL dock.

On about 13 January 2014, the B100 gelled a second time. On 15 January 2014, the test team added diesel to the BUSL fuel tanks, with a resulting blend of 70 percent biodiesel (B70), later confirmed by fuel analysis. Adding diesel reversed the gelling, and no further incidence of gelling was reported for the remainder of testing.

When developing the test plan, the test team made the assumption that a combination of factors would prevent the fuel temperature from falling below the specified 33.5 °F cloud point temperature. This approach may have underestimated the conduction effect from topside hull and deck areas exposed to severe cold air temperatures. The test team looked at past studies for gelling issues, and these studies (Army Corps of Engineers [ACOE] and NOAA Great Lakes) made no mention of additive use for cold weather operations. The ACOE installed heaters on their external tanks to keep the B100 warm, and the fuel vendors did not supply B100 in the cold weather months. Furthermore, except for icebreaking assets and bulk carriers, most Great Lakes vessels do not operate in the cold winter months when much of the waters are ice covered. A number of options may be used to avoid gelling, such as: (1) installing fuel heaters, (2) switching fuel seasonally, and (3) blending biodiesel with B0. Likewise, the challenges and logistics of storing thousands of gallons of biodiesel at a CG site were not examined in this study. Such storage is likely to require special attention, especially to prevent gelling, considering many storage tanks are above ground and unheated.

3.2.4 Comparative Carbon Footprint and Emissions Summary

ORNL conducted air emissions and carbon footprint analyses to estimate whether changing fuels from B0 diesel to B100 biodiesel could significantly support the Coast Guard's compliance with EO 13514. ORNL conducted the emissions analysis based on a review of literature available on heavy duty engines of a similar technology level to the model year 1997 propulsion engines on the BUSL. Limitations of this analysis are:

- No data are available for marine engines produced around 1997. ORNL used data for on-road engines.
- Most studies used 20 percent biodiesel (B20).
- The BUSL duty cycle differs substantially from both the on-road duty cycles, where most of the emissions data were collected, and from the Tier 1 emissions standards for general purpose marine engines. The BUSL spends 80-85 percent of its duty cycle under idling conditions, such as when it is on station servicing buoys. ORNL estimated, however, that idling operations comprises only 15-20 percent of the total fuel consumed.

The ORNL analysis is based on measured stack emissions from other engines that are similar to the Cummins 6CTA8.3 M1 engine, which is a pre-Tier 1 emissions model. Assuming the BUSL engine characteristics are identical to a similar 2001 Tier 1 model, ORNL projected that use of B100 in the Cummins 6CTA8.3 M1 engine would reduce emissions on a mass basis for a given amount of power delivered from the engine. Carbon monoxide (CO) emissions would be reduced by 48.1 percent, hydrocarbon (HC) emissions by 67.4 percent, and particulate matter (PM) emissions by 47.2 percent. NOx emissions, on the other hand, would increase by 10.3 percent. ORNL also found that the emissions response of an individual engine to biodiesel may vary considerably about a mean value. Overall, B100 use will reduce pollutant emission concentrations and masses.

ORNL used the Federal Energy Management Program's (FEMP) annual GHG and Sustainability Data worksheet to estimate net carbon footprints from burning fuels derived from well or field sources. The FEMP approach gives credit for fuels derived from plant matter; (the B100 portion of biodiesel blends) that reclaim CO_2 from the atmosphere (i.e., recycled CO_2) that may have earlier been released by combustion. Fuels derived from oil drilling would not receive credit because their combustion represents a net addition to CO_2 in the atmosphere. The FEMP worksheet calculated that for a standard BUSL trip in which 100 gallons of fuel were consumed, switching from diesel to biodiesel would reduce anthropogenic CO_2 emissions from 925.2 kg to 0.82 kg. Although the combustion of biodiesel releases a similar mass (923 kg) of CO_2, that mass is derived from plant material that had recently been taken up from the atmosphere. The net addition (0.82) accounts for the field-to-pump consumption of anthropogenic carbon upstream of the B100 consumption in the vehicle.

ORNL also examined more comprehensive lifecycle approaches that contrast CO_2 release from biodiesel production from waste vegetable oil against the release from petroleum diesel production. ORNL cited recent lifecycle estimates that showed GHG footprint reductions for waste cooking oil ranging between 65.9 percent and 76.8 percent and up to 85 percent relative to petroleum diesel fuel. ORNL also reported literature that showed an average 3.1:1 ratio of energy production to consumption from biodiesel farming and fuel production.

In summary, the ORNL analysis suggests that emissions from biodiesel fueled engines pose two benefits compared to diesel. First, biodiesel emissions (CO, HC & PM) contain lower levels of pollutants with the exception of NOx. Second, because biodiesel contains carbon that has been derived from plant sources, its emissions represent a much smaller net contribution to atmospheric GHG levels. It should be noted that modern diesel engines, such as the Cummins QSX15 (675HP) will soon achieve Tier 4 emissions standards. Although marine engines have limited exemptions with regard to federal emission standards, the technology of the newer diesel engines coupled with the use of biodiesel can reduce the effective GHG to almost zero.

3.2.5 Fuel Quality and Logistics

The quality of the delivered fuel was monitored via fuel sample analyses performed by the RDC and the fuel supplier through testing laboratories. The analysis results are shown in Table 10. Although fuel quality issues arose during testing, and are discussed below, those issues did not halt or impact testing, and did not appear to affect boat operation. In addition, some fuel samples were taken directly from the BUSL fuel tanks. Those results are shown in Table 10. Shading is used in the fuel tables (Tables 10, 11 and 12) for readability to show each delivery as one event.

3.2.5.1 Oxidative Stability

B100 fuel delivered on 5 February 2013 (first delivery) failed the oxidative stability analysis (at 0.79 hr, 1.96 hr, and 1.72 hr for three samples, well below the 3-hour minimum). BiodieselOne adjusted the dosing (using an antioxidant) to correct this problem, which was not experienced on subsequent deliveries. During inactive operational periods, oxidation stability results from samples taken from the BUSL fuel tanks were slightly below the standard for fuel deliveries (2.41 hr and 2.79 hr). The test team estimated that the fuel in the tanks was more than two months old, and considered the lowered readings to reflect normal aging of the fuel. The BUSL resumed its operations using this older fuel after the government shutdown-imposed operating restrictions were lifted. This fuel had no apparent adverse impact on the operation of the BUSL.

3.2.5.2 High Sulfur

B100 fuel delivered on 5 February 2013 (first delivery) failed the sulfur analysis (at 44 ppm, well over limit of 15 ppm) and the UCONN lab tested it to be equivalent to B97, not B100. The test team determined the cause was use of a truck that had previously been used to deliver standard #2 home heating oil. The truck and its pumping/delivery system had not been purged and cleaned after the delivery, and residual #2 oil contaminated the B100 that was pumped into the BUSL. To avoid this problem in future deliveries, the fuel supplier developed a tote tank delivery system (box truck with two 275 gallon B100-dedicated totes). This change provided uncontaminated containers to transport the delivery of biodiesel to the ANT, and better control for dosing as needed to affect test parameters. Using this system, no further high sulfur test results were received.

Table 10. B100 delivery truck fuel test results.

			Delivery/Sample Date >>	2/5/13	3/11/13	3/11/13	4/29/13	5/10/13	5/21/13	9/3/13	9/30/13
			Gallons Delivered >>	766.0	481.6		450.0	475.0	500.0	350.0	300.0
			Sampled by >>	RDC	BioOne	RDC	BioOne	RDC	BioOne	BioOne	No Test
			Testing Lab >>	UCONN	UCONN	UCONN	Gorge	UCONN	UCONN	UCONN	
Flash Point, Closed Cup	ASTM D93	93 min	° C	153.3	167.1	168.9	165.0	160.1	179.9	150.0	
Water and Sediment	ASTM D2709	0.05 max	% volume	0	0	0	<.005	0	0	0	
Kinematic Viscosity @ 40°C	ASTM D445	1.9-6.0	mm2/s	4.708	NT	4.752	4.721	NT	NT	NT	
Sulfated Ash	ASTM D874	0.02 max	% mass	<0.01	NT	<0.005	<0.005	NT	NT	NT	
Sulfur											
S 15 Grade	ASTM D5453	15 ppm max	ppm	43.6	NT	2.5	4.3	8.7	1.5	12.2	
S 500 Grade	ASTM D5453	500 ppm max	ppm	NT	NT	NT	NT	NT	NT	NT	
Copper Strip Corrosion	ASTM D130	No 3 max	rating	1A	NT	1A	1A	NT	NT	NT	
Methanol Content	EN 14110	0.20 max	% volume	0.003	NT	0.004	NT	NT	NT	NT	
Cetane Number	ASTM D613	47 min		NT	NT	NT	51.3	NT	NT	NT	
Cloud Point	ASTM D2500	report to cust.	° C	-1.2	-1.8	-1.6	NT	NT	0.2	1.1	
Carbon Residue	ASTM D4530	0.05 max	% mass	0.038	NT	0.033	<.0002	NT	NT	NT	
Acid Number	ASTM D644	0.50 max	mg KOH/g	0.170	0.270	0.274	0.22	0.267	0.205	0.322	
Free Glycerine	ASTM D6584	0.02	% mass	0.035	0.00	0.001	0.002	0.003	0.002	0.002	
Total Glycerine	ASTM D6584	0.24	% mass	0.165	0.179	0.179	0.188	0.183	0.166	0.179	
Phosphorus	ASTM D4951	10 max	ppm	<0.001	NT	<0.001	<.0001	NT	NT	NT	
Vacuum Distillation End Point	ASTM D1160	360° C max	° C	NT	NT	346.5	NT	NT	NT	NT	
Oxidative Stability	EN 14112	3 min	hours	0.79	1.96	1.72	27.2	16.4	5.31	3.1	
Cold Soak Filtration	Annex to D6751	360 max	seconds	146	149.6	125	123	109.9	168.7	152	
Calcium & Magnesium (comb.)	EN 14538	5 max	ppm	4.5	NT	<0.5	2	NT	NT	NT	
Sodium & Potassium (comb.)	EN 14538	5 max	ppm	<0.1	NT	<0.05	<2.0	NT	NT	NT	
Test	**Method**	**Limits**	**Units**								

Notes: 1. Values in red represent out of spec test results 2. NT = not tested

Table 10. B100 delivery truck fuel test results (cont.).

			Delivery/Sample Date >>	10/28/13	10/28/13	11/18/13	11/25/13	11/25/13	12/4/13	12/11/13	12/23/13
			Gallons Delivered >>	500.0		325	550		275	275	252
			Sampled by >>	BioOne	RDC	RDC	BioOne	RDC	RDC	No Test	RDC
			Testing Lab >>	UCONN	UCONN	UCONN	UCONN	UCONN	UCONN		UCONN
Flash Point, Closed Cup	ASTM D93	93 min	° C	153.0	159.0	167.0	160.8	168.8	165.5		156.9
Water and Sediment	ASTM D2709	0.05 max	% volume	0	0	0	0	0	0		0
Kinematic Viscosity @ 40°C	ASTM D445	1.9-6.0	mm2/s	NT	4.670	4.679	NT	4.535	4.656		4.665
Sulfated Ash	ASTM D874	0.02 max	% mass	NT	<0.02	<0.001	NT	<0.001	<0.001		<0.001
Sulfur											
S 15 Grade	ASTM D5453	15 ppm max	ppm	5.5	12.4	4.6	6.8	3.7	3.3		4.3
S 500 Grade	ASTM D5453	500 ppm max	ppm	NT	NT	NT	NT	NT	NT		NT
Copper Strip Corrosion	ASTM D130	No 3 max	rating	NT	1A	1A	NT	1A	1A		1A
Methanol Content	EN 14110	0.20 max	% volume	NT	0.003	0.004	NT	0.003	0.004		0.004
Cetane Number	ASTM D613	47 min		NT	NT	NT	NT	NT	NT		NT
Cloud Point	ASTM D2500	report to cust.	° C	0.3	0.7	0.8	-0.4	-0.1	-0.78		0.1
Carbon Residue	ASTM D4530	0.05 max	% mass	NT	0.021	0.030	NT	0.029	0.016		0.018
Acid Number	ASTM D644	0.50 max	mg KOH/g	0.470	0.261	0.240	0.457	0.271	0.275		0.248
Free Glycerine	ASTM D6584	0.02	% mass	0.006	0.002	0.001	0.005	0.001	0.002		0.003
Total Glycerine	ASTM D6584	0.24	% mass	0.233	0.167	0.153	0.184	0.152	0.169		0.159
Phosphorus	ASTM D4951	10 max	ppm	NT	<0.001	<0.001	NT	<0.001	<0.001		<0.001
Vacuum Distillation End Point	ASTM D1160	360° C max	° C	NT	347.9	346.5	NT	347.7	350.0		348.9
Oxidative Stability	EN 14112	3 min	hours	>31.3	2.41	5.33	>24	2.52	3.47		8.7
Cold Soak Filtration	Annex to D6751	360 max	seconds	154.3	130.0	357.3	119.4	142.3	110.0		152.3
Calcium & Magnesium (comb.)	EN 14538	5 max	ppm	NT	3.1	2.7	NT	3.3	2.7		2.9
Sodium & Potassium (comb.)	EN 14538	5 max	ppm	NT	2.4	0.5	NT	0.8	<0.5		<0.5
Test	**Method**	**Limits**	**Units**								

Notes: 1. Values in red represent out of spec test results 2. NT = not tested

Table 11. B100 BUSL fuel tank test results.

			Delivery/Sample Date >>	7/19/13	9/9/13	12/19/13	1/16/14
			Gallons Delivered >>				
			Sampled by >>	RDC	RDC	RDC	RDC
			Testing Lab >>	UCONN	UCONN	UCONN	UCONN
Flash Point, Closed Cup	ASTM D93	93 min	° C	157.1	158.0	156.3	NT
Water and Sediment	ASTM D2709	0.05 max	% volume	0	0.03	0	NT
Kinematic Viscosity @ 40°C	ASTM D445	1.9-6.0	mm2/s	4.6	4.651	4.639	NT
Sulfated Ash	ASTM D874	0.02 max	% mass	NT	NT	<0.005	NT
Sulfur							
S 15 Grade	ASTM D5453	15 ppm max	ppm	8.9	14.9	3.7	NT
S 500 Grade	ASTM D5453	500 ppm max	ppm	NT	NT	NT	NT
Copper Strip Corrosion	ASTM D130	No 3 max	rating	NT	NT	1A	NT
Methanol Content	EN 14110	0.20 max	% volume	NT	NT	0.003	NT
Cetane Number	ASTM D613	47 min		NT	NT	NT	NT
Cloud Point	ASTM D2500	report to cust.	° C	1.0	1.1	-0.5	-4.2
Carbon Residue	ASTM D4530	0.05 max	% mass	NT	NT	0.026	NT
Acid Number	ASTM D644	0.50 max	mg KOH/g	0.390	0.311	0.262	NT
Free Glycerine	ASTM D6584	0.02	% mass	0.001	0.002	0.002	NT
Total Glycerine	ASTM D6584	0.24	% mass	0.168	0.139	0.151	NT
Phosphorus	ASTM D4951	10 max	ppm	NT	NT	<0.001	NT
Vacuum Distillation End Point	ASTM D1160	360° C max	° C	NT	NT	350	NT
Oxidative Stability	EN 14112	3 min	hours	2.1	5.17	2.79	NT
Cold Soak Filtration	Annex to D6751	360 max	seconds	120	169.8	120.6	NT
Calcium & Magnesium (comb.)	EN 14538	5 max	ppm	NT	NT	1.1	NT
Sodium & Potassium (comb.)	EN 14538	5 max	ppm	NT	NT	<0.5	NT
Test	**Method**	**Limits**	**Units**				

Notes: 1. Values in red represent out of spec test results 2. NT = not tested

3.2.5.3 Fuel Delivery

B100 deliveries were made monthly from February through May of 2013 with an average of 500 gallons per delivery. Deliveries were suspended in June due to operating hour restrictions driven by federal budget issues. In September, operations resumed and deliveries began and continued through December of 2013. Table 12 details the delivery dates and quantity delivered.

Table 12. B100 deliveries.

Delivery Date	2/5/13	3/11/13	4/29/13	5/10/13	5/21/13	9/3/13	9/30/13	10/28/13	11/18/13	11/25/13	12/4/13	12/11/13	12/23/13	Total
Gallons	766.0	481.6	450.0	475.0	500.0	350.0	300.0	500.0	325	550	275	275	252	5499.6

During most of the operational testing, the Coast Guard's goal was to operate the BUSL on pure B100. The desire to avoid the presence of even small amounts of conventional diesel was to identify the implications of pure biodiesel use. . Although assessing the fuel supply chain was not an objective of the project, a lesson learned from our experience is that although B100 is in wide use, suppliers providing a small amount of B100 may find it cost prohibitive to dedicate a tank truck for B100 use, which in turn may lead to unconventional delivery methods. On the other hand, a dedicated B100 delivery truck might not be required in actual implementation as residual amounts of diesel or home heating oil may be acceptable.

3.2.6 Crew Feedback

During every visit to the BUSL, the test team interviewed the crewmembers and engineers that had day-to-day contact and experience with the BUSL to gain insights to any differences noted between B100 and diesel. They were asked specifically if they noticed any performance difference between the two fuels, and unanimously agreed that they could not discern any difference. The only way they knew they were burning B100 was that the exhaust smoke appeared thicker and whiter, and smelled like “french fries”.

Some crewmembers indicated that the thicker smoke was a little more irritating when there was no wind and the smoke lingered, but it did not affect the safety of the buoy operations. Some of the crewmembers said that the smoke irritated their eyes, but later confirmed that the diesel smoke also irritated their eyes. One crewmember initially complained of getting headaches from the biodiesel exhaust smoke, but this could not be attributed to the smoke. It was mentioned at the beginning of the operational testing, but was not brought up later.

4 B100 IMPLEMENTATION CONCLUSIONS AND RECOMMENDATIONS

4.1 Conclusions

Based on the testing in this study, B100 could be an alternative fuel in the BUSL if fuel gelling issues are mitigated and managed. A break-in period is required to ensure engine and fuel system compatibility with this alternative fuel. The most significant issue experienced during testing was gelling of the B100, which clogged fuel filters and caused the main engines and generator to shut down while underway. Gelling can be prevented through fuel management (e.g., fuel additives, shifting to a diesel/biodiesel blend), or through design (e.g., insulation, tank heaters, etc.). A break in period is also required to ensure engine and fuel system compatibility with this type of alternative fuel.

The long term effects of B100 on engine and fuel system life still need to be determined. Using engine RPM, temperature and fuel consumption as metrics, and crew observations as additional input, B100 use did not significantly impact engine or boat performance, long-term maintenance, or operational capability. Although the lack of maintenance issues and the support of previous studies strongly suggest that long term maintenance is not an issue, we acknowledge that a one-year test is a short time frame, compared with the expected service life of marine diesel engines and CG boats. No operational changes, except for those that were noted, were imposed by the use of B100 and no additional maintenance was needed. Crew feedback indicates that B100 use does not pose significant impacts to crew safety.

ORNL’s emissions analysis, suggests that B100 emissions (CO, HC & PM) contain lower levels of pollutants with the exception of NOx, and because B100 contains carbon that has been derived from plant sources, the emissions represent a much smaller net contribution to atmospheric GHG levels. These conclusions are generally consistent with previous NOAA and Washington State Ferries (WSF) studies, indicating benefits from using B100, including:

- Lower engine exhaust emissions
- Reduced impact of spilled fuel: biodiesel biodegrades at roughly the same rate as sugar (dextrose) and more than 3 times more quickly than diesel
- Improved health and safety: non-offensive odor, no carcinogens, higher flash point
- Improved engine performance: biodiesel is a cleaner fuel with a higher cetane number and better lubricity properties than conventional diesel fuel

- Reduced system maintenance: biodiesel's higher lubricity causes less injector and fuel pump wear

4.2 Recommendations

This project's focus was to determine whether the BUSL, and in turn other USCG boats, can use B100 as an alternative to regular diesel fuel. Our conclusion is that B100 can be used as an alternative fuel on a case by case basis, if the fuel gelling problems are mitigated. The principal limitations are imposed by low ambient air and water temperatures, and by some materials incompatibilities. The following recommendations will help minimize these limitations, and allow for expanded biodiesel use in the future.

4.2.1 Certification and Break-in Period

Prior to using B100 for the first time, the engine and fuel system should be certified to burn B100. This involves cleaning deposits from fuel tanks and fuel lines, and identifying parts that are not compatible with B100, finding compatible replacement parts, installing the parts and running the engines during a break-in period. The break-in period is needed to detect and correct any issues that may occur due to (1) incompatible parts remaining in the system, and (2) dissolved and re-deposited carbon deposits. The break-in period should include additional checks for leaks and other unusual conditions, e.g., premature fuel filter clogging.

4.2.2 Cold Weather Operations

B100 must be maintained above the cloud point to avoid gelling, which can make the fuel unusable and present operating difficulties. This may be accomplished by heating the fuel through boat equipment changes, changing to a different fuel, or blending B100 with diesel, for example. In this study, a blend equivalent to B70 resolved gelling issues. Gelling in the transport or bulk storage off the boat must also be managed, although these issues were not part of this study, and there was no shore-side B100 storage at the CG test unit. Fuel gelling needs to be managed properly, because it may seriously impact crew and boat safety if it occurs on an operating CG boat.

4.2.3 Fuel Quality and Logistics

Assessing the fuel supply chain was not within the scope of this study, however some issues became apparent during the testing. First, although B100 is commercially available, it is produced generally by small production facilities, and quality may vary significantly. In addition, the type of feedstock used in production drives the cost and properties of the product. A robust fuel sampling and analysis program should accompany a B100 implementation program to ensure the fuel meets the established requirements, and use of additives should be considered when developing a fuel quality plan. The certification of the supplier is also important. Suppliers should be listed by the National Biodiesel Board (www.biodiesel.org) or have BQ-9000 certification.

4.2.4 Implementation Costs

Further study is needed to assess the cost of implementing B100 in the CG on various boat classes as each boat class will be different costs associated with them. Costs were reported to change out incompatible parts and to instrument the BUSL for testing purposes. Furthermore, B100 fuel supply is subject to factors that can affect the price significantly but are difficult to predict. An example is the expiration of a federal subsidy just after the testing was completed that would increase the fuel price by 33 percent.

4.2.5 Crew Health

Occupational health monitoring should be included in any future implementation plan. While no adverse crew effects were documented in this study, we recognize that the limited scope (low number of crew participants, and relatively short duration) does not provide an adequate basis for conclusions regarding long term health effects.

4.2.6 Extrapolation to Other Classes of Diesel Powered Craft

The extent to which test results on the BUSL can be extrapolated to existing newer, high speed boats, such as the RB-M is unknown. Class specific testing or controlled small scale implementation is recommended for other classes. Later model year emission compliant diesel engines with higher injection pressures and tighter fuel system tolerances may be more sensitive to operation with high biodiesel blends. The engine manufacturer can be consulted to determine the amount of biodiesel that the engine can tolerate and still meet required emission limits. Previous USCG Cutter experience utilizing biodiesel blends (B5) in District 9 resulted in temporary shutdowns due to fuel management and gelling issues. Since cutters were not within the scope of this project, biodiesel blends are not recommended for diesel powered craft unless fuel gelling issues are mitigated.

For any new builds or designs of diesel boats to be built in the future, the following features should be considered in its design such that B100 or any partial blends (B5, B20, etc.) could considered a possible fuel:

- Fuel tank heaters
- Fuel line heaters
- Separation of fuel tanks from coldest portions of the hull or direct contact
- Biodiesel compatible fuel system parts to supply MDE's and generators

The incorporation of these features during the design process would allow CG decision makers the ability to have as an option the use biodiesel fuel or its blends at any time through their operational lives.

5 REFERENCES

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APPENDIX A DRAFT BUSL TIME COMPLIANCE TECHNICAL ORDER (TCTO)

Draft BUSL Time Compliance Technical Order (TCTO):

Data for Input to TCTO Phase 1 Form (Section 1)

Contract No. HSCG32-10-D-R00021
Task Order HSCG32-11-J-300018, Deliverable 2
Project 4103 – Operational Testing of Alternative Fuels

27 January 2012

1. Case File #: [leave blank]
2. TCTO #: [leave blank]
3. Type: BUSL
4. Title: Modification for Alternative Fuel Testing (Biodiesel) on CG49410
5. Submitted by: Coast Guard Research and Development Center
6. Submission Date: [leave blank]
7. Desired Installation Date: 1 August 2012
8. Requirement/Description: See Table 1, which lists changes recommended to CG49410 prior to commencement of biodiesel (B100) testing. Table 2 provides cost details for each item.

Table A-1. Recommended changes to BUSL CG49410 to support B100 testing.

Task	Description	Rec.	May be needed	Comments
1	Fuel Tanks			
a	Thoroughly clean BUSL fuel tanks before loading the B100 fuel.	X		Cleaning the fuel tanks will help prevent fuel filter clogging, possible damage to engine fuel pump and fuel injectors, and contamination of the B100 fuel. Will reduce initial fuel filter replacement requirements.
2	Fuel System Modifications			
a	Replace Aeroquip FC-234 fuel line flex hoses with B100-compatible hoses.	X		Replace with Aeroquip 2807 hose (Coast Guard approved Teflon inner tube hose).
b	Change out Racor 75-500 MAX dual filter assemblies.	X		Install dual Racor 777R heated filter assemblies and 3-way valve. These use the engine coolant and 24 VDC to heat the filter assembly and fuel. They also have biodiesel compatible filter elements.
c	Replace Buna-N O-ring in the CPV union fitting H849-12, 3/4" OD, weld type, O-ring face seal (Item #8 Fuel System Materials List).	X		The O-ring inside the H849-12 is an AS568-019 size, replace with Viton O-Ring. Can be purchased from CPV Manufacturing, Inc. (Philadelphia, PA) for replacement O-rings. POC: Sales Manager; E-mail: C_Horter@cpvmfg.com This was not replaced because it was not in contact with the fuel, re: RDC
d	Replace BUSL fuel tank access hole gaskets with B100-compatible gaskets.	X		Replace with Viton gasket. Can be procured from McMaster-Carr. Refer to order number #58055. .
e	Install Artic Fox ™ fuel line heaters model I-909BT-B100 between fuel tanks and filter assembly.	X		For enhanced cold weather operation. Heat exchanger assures fuel from tank is heated to correct temperature before entering engine and cools returning fuel so there is no precipitation in the fuel tank from the warm fuel mixing with the colder fuel. Water temperatures at LIS indicate 37 °F in January and February. Cummins recommends cloud point 11 °F below lowest ambient temperature at which fuel is expected to operate. Fuel is expected to have a cloud point of 32 °F so may not be a problem. If fuel tanks and fuel line are heated to above 42 °F, then we are OK.

Table A-1. Recommended changes to BUSL CG49410 to support B100 testing (cont.).

Task	Description	Rec.	May be needed	Comments
3	Instrumentation			
a	Install fuel flow meters for fuel consumption comparison between the baseline diesel fuel and the B100 and for tracking B100 performance.	X		FlowScan model N2TD-6BB-2K and all associated parts will be installed by FlowScan.
b	Install shaft torque instrumentation for recording shaft horsepower for comparison between baseline diesel fuel and B100.	X		ShaftMaster 1000 Data collection unit and all associated parts to be installed by Industrial Hillhouse Marine Inc., Sanbornton, NH. POC: Rodney Hillhouse, 603-566-4330.
c	Replace analog FWMurphy™ sending units with FWMurphy ES-2T sending units. Install FWMurphy PV750 Engine Display/Monitoring System.	X		Connect FWMurphy PV750 to data collection computer in nav box to record engine data to monitor BUSL performance on the B100 fuel and for comparison with the baseline diesel fuel.
d	Install nav box in compatible location.	X		Nav box will have a weather station with integrated GPS L1 receiver, power supply/ converter, and inertia measurement unit and data collection computer inside a SKB NEMA 4 enclosure.
4	Engine Modifications			
a	Change out existing paper type medium (Fram style model number P-4102A) elements in the engine fuel filters. (Also Cummins #3903640)	X		Replace with Cim-Tek® Biodiesel Bio-Tek Hydroglass Filter CIM800BHG02-70037. Can be procured from www.jmesales.com.
b	Replace seals and gaskets on the Cummins engines; i.e., head gasket, etc.		X	A detailed list of the bill of materials for each engine has been formulated. Cummins willcontact the respective suppliers of each of these components to assess their compatibility.
5	Miscellaneous			
a	Provide extra fuel oil filters.	X		They are needed for anticipated increased use from the cleaning action of the B100 fuel.
b	Restore BUSL to pre-demonstration configuration.	X		If the BUSL is not going to remain in B100 service, restore it to original configuration.

Table A-2. Cost details for each TCTO item.

TCTO Line #	Item/Service	Suggested Manufacturer	Suggested Part Number	Qty	Cost Each	Sub-Total	Install. Cost	Total Cost	Notes
1a	Tank cleaning/ stripping	CTR Tank Cleaning/Repair	N/A	1	$1,200	$1,200	N/A	$1,200	Will give full estimate once committed
2a	B100 fuel lines-flexible (size 06)	Aeroquip	2807 Teflon Lined	1 lot	$1,423	$1,423	$0	$1,423	CG-approved and includes end fittings. Lot = (2) 7 ft, (1) 6 ft, (5) 4 ft, and (1) 1.5 ft length. Installation to be done by Ship's Force.
2a	B100 fuel lines-flexible (size 12)	Aeroquip	2807 Teflon Lined	1 lot	$748	$748	$0	$748	CG-approved and includes end fittings. Lot = (1) 4 ft and (1) 10 ft length. Installation to be done by Ship's Force.
2b	Heated filter assemblies	RAYCOR	777R	7	$600	$4,200	$0	$4,200	Unit should be able to install these.
2c	B100 compatible O-rings	CPV Manufacturing Inc.	AS568-019 size	2	$25	$50	$0	$50	$50 = Min order from CPV Manufacturing; O-rings ~$1.00 or $2.00 if ordered from supplier. Installation to be done by Ship's Force.
2d	B100 compatible gaskets (fuel tank access hole)	McMaster Carr	Order # 58055	2	$567	$1,134	$0	$1,134	Quote from McMaster Carr; Viton gasket: 26.5" (OD) 20.5"(ID), 3/16" thick. Thirty (30) bolt holes evenly spaced: 1/8" thick = $254.11/gasket. Installation to be done by Ship's Force.
2e	Inline fuel heaters	Artic Fox	I-909BT-B100	4	$600	$2,400	$1,500	$3,900	One spare miscellaneous installation parts estimated.
3a	Fuel monitoring system	FlowScan	N2TD-6BB-2K	1	$5,953	$5,953	$0	$5,953	2 MDE, 1 Genset; installation to be done by Ship's Force.
3b	Shaft power/torque instrumentation	HillHouse ShaftMaster	Custom build	1	$7,500	$7,500	Included	$7,500	$10K if system stays after test.

Table A-2. Cost details for each TCTO item (cont.).

TCTO Line #	Item/Service	Suggested Manufacturer	Suggested Part Number	Qty	Cost Each	Sub-Total	Install. Cost	Total Cost	Notes
3c	Engine data display/recorder	FWMurphy	PV750	3	$520	$1,560	$1,600	$3,160	Installation to be done by local dealer; estimated at 2 days
3d	Nav box	SDK, Moxa, Mountain Weather Station		1	$4,300	$4,300	$0	$4,300	Install to be done by test team; estimated 4 hrs.
4a	B100 compatible secondary fuel filters	Cim-Tek	CIM800B HG02-70037	30	$40	$1,200	$0	$1,200	Quantity may change after field test.
4b	Cummins Engines gaskets, seals, O-rings	Cummins suppliers	TBD	3	$500	$1,500	$0	$1,500	This is best guess. Cummins to supply better cost estimate. Installation to be done by Ship's Force.
5a	Replacement filters	RAYCOR	6732	30	$20	$600	$0	$600	Estimated quantity; may change after field test.
N/A	Spill Kit	ENPAC	1362-YE	2	$400	$800	N/A	$800	Same company that TRACEN uses. This is the 65 gal response kit.
								$37,668	**Total Estimate for BUSL**

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APPENDIX B ORNL REPORT

Analysis of Criteria and Greenhouse Gas Emissions of U.S. Coast Guard use of Waste Cooking Oil Biodiesel on the 49' BUSL

James Szybist, Scott Curran, and John Storey

Oak Ridge National Laboratory

August 24, 2012

Executive Summary

The U.S. Coast Guard is working towards using 100% biodiesel derived from waste cooking oil on their 49' Buoy Utility Stern Loading (BUSL) boat in an effort to come into compliance with Executive Order (EO) 13524. At the request of The Coast Guard Research and Development Center (RDC), the National Transportation Research Center at the Oak Ridge National Laboratory (ORNL) has conducted this analysis to help the Coast Guard determine whether this change can significantly support the Coast Guard's compliance with the EO. The purpose of this report is to estimate the impact of biodiesel on criteria emissions and greenhouse gas (GHG) emissions based on previously published literature.

We concluded that 100% biodiesel reduces emissions of carbon monoxide (CO), unburned hydrocarbons (HC), and particulate matter (PM) while slightly increasing the emissions of nitrogen oxides (NO_X). On average, there is a 48.1% reduction in CO, 67.4% reduction in HC, a 47.2% reduction in PM, and a 10.3% increase in NO_X emissions on a mass basis for a given amount of power delivered from the engine. We also found that there is a significant amount of scatter in the data with regards to the emissions response of an individual engine to biodiesel.

The BUSL duty cycle differs substantially from both the on-road duty cycles where most of the emissions data was collected, and from the Tier 1 emissions standards for general purpose marine engines. Specifically, the BUSL spends 80-85% of its duty cycle under idling conditions. However, this comprises only 15-20% of the total fuel consumed. Additionally, while we found that the engine operating condition can impact emissions, and in particular the response to biodiesel, we concluded there is insufficient data in the open literature to further refine the BUSL emission response based on its duty cycle.

The Federal Energy Management Program (FEMP) GHG and Sustainability Data reporting methodology currently used by the federal government for reporting GHG emissions, as required by EO 13254 is used. An average BUSL trip consuming 100 gallons of petroleum-derived diesel fuel releases 925.2 kg of reportable anthropogenic CO_2e emission. The same trip with biodiesel produces 0.82 kg, nearly a 100% removal of the reportable anthropogenic CO_2e emissions. The NTRC was also asked to investigate the anthropogenic emissions that would be calculated by potential future lifecycle approaches, with the understanding that that biodiesel derived from

waste vegetable oil will be used by the Coast Guard. The FEMP reporting methodology does not currently distinguish between different biodiesel source materials (i.e., soy vs. waste cooking oil), but future changes are possible if a lifecycle analysis methodology is used in the future. Considerations to the different lifecycle emissions are made within this report, with waste cooking oil biodiesel having more favorable lifecycle GHG emissions.

Introduction

Executive Order (EO) 13514-*Federal Leadership in Environmental, Energy, and Economic Performance* mandates that all Federal agencies establish an integrated strategy towards sustainability and the reduction of GHG [1]. In an effort to come into compliance, the U.S. Coast Guard will be testing 100% waste cooking oil biodiesel in its 49' BUSL boats. The Coast Guard Research and Development Center requested the services of the Oak Ridge National Laboratory's National Transportation Research Center to analyze the emissions implications of changing from a petrochemical to biodiesel, in order to inform the decision on whether this shift in the BUSL fleet is in the Coast Guard's interest. This report documents ORNL's literature-based analysis on the impact of this fuel change on both criteria emissions (unburned hydrocarbons, carbon monoxide, particulate matter, and NO_X) and greenhouse gas emissions.

A wealth of data exists on the impact of biodiesel on criteria emissions in the current literature. The focus of this literature survey is on heavy duty engines of a similar technology level so as to be as relevant as possible. Additionally, impacts of the duty cycle of the BUSL are considered.

For GHG emissions, EO 31514 uses the 100-year global warming potential (GWP) values to convert the non CO_2 GHG's to units of CO_2 equivalent (CO_2e). The three GHGs that result from mobile sources are CO_2 (GWP =1), CH_4 (GWP = 21) and N_2O (GWP =310) [2]. CO_2 emissions make up the vast majority of the CO_2e emissions from mobile sources but the high GWP factor for CH_4 and N_2O mean even small amounts of these emissions can impact the CO_2e emissions. EO 13514 requires GHG reductions in Scope 1, Scope 2 and Scope 3 emissions with Scope 1 emissions being those emissions that result directly from agency activities including generation of electricity, mobile sources and fugitive emissions, Scope 2 emissions being indirect emissions such as those from purchased electrical power, and Scope 3 emissions being indirect emissions not covered in Scope 2 such as those associated with employee commuting and travel [3]. Section 8 of EO 13514 requires that all agencies develop a Strategic Sustainability Performance Plan detailing sustainability goals and GHG reduction targets to be achieved through the end of fiscal year (FY) 2020 relative to a FY 2008 baseline. These reduction targets are in addition to the petroleum energy use decrease and alternative fuel use increase mandates established by EO 13423 and EISA. The Department of Homeland Security (DHS) Strategic sustainability Plan sets Scope 1 & 2 reduction targets of 25% by 2020.

Chapter 6 of the EO 13514 Federal Fleet Management Handbook states that B100 is considered an alternative fuel and is ideal for locations with high diesel fuel consumption [4]. The BUSL emissions fall under Scope 1 mobile sources: emissions that result from the combustion of fuels in agency-controlled mobile combustion sources (e.g., automobiles, ships, and aircraft) including CH_4 and N_2O emissions from biofuel combustion (anthropogenic component).

BUSL Characteristics and Applicable Emission Regulations

The BUSL boats are each equipped with twin diesel engines for propulsion and a generator engine for electricity production. Specifications for the BUSL boat, including information about the engines, are given in Table 1.

Table 1. BUSL and engine characteristics taken from Reference [5].

Operational Characteristics		Physical Characteristics	
Range	400 NM[1] @ 10 knots	LOA[2]	49'-2 ¼"
Max Speed	10.5 knots @ 2300 RPM	Beam (Maximum)	16'-10"
Cruise Speed	7 knots	Draft (Full Load)	5'-4"
Bollard Pull	11,000 pounds, Aft 8,300 pounds, Bow	Propulsion	Two, Cummins, 6CTA8.3 M1 (305 horsepower each)
Max Range	400 NM @ 10 knots	Generator	20 kW[3], Single Phase, 60 Hz[4], 120 volts alternating current @ 1800 RPM
Fuel Consumption	100 gallons/trip 600 gallons/month	Generator Engine	Cummings ONAN 4B3.9 21 kW
		Fuel Tank Capacity	783 gallons @ 95%
		Number of Fuel Tanks	2
		Crew	Four Crew, Three Spare/Passenger
		Deckhouse	Aluminum
		Hull	A-36 Steel

[1]nautical miles
[2]Length overall
[3]kilowatt
[4]Hertz

The propulsion engines on the BUSL boat were manufactured by Cummins and are from model year 1997. No EPA rules regulated emission levels from general purpose marine engines for either military or non-military applications for model year 1997, thus there is no publically available emissions data from Cummins.

Emissions regulations for general purpose marine engines were first put in place by the 1999 Marine Engine Rule, passed in November 1999, and took effect for model year 2001 and newer engines. Because of the regulation, Cummins made the emissions data from the 2001 version of

the 6CTA8.3-M Tier 1 compliant engine publically available. For the purposes of this analysis, we will assume that the emissions of the 2001 CTA8.3-M engine are representative of the 1997 CTA8.3-M1 engine. The complete marine engine performance curve and specifications of the 2001 engine are given in Appendix A. It is worth noting that the model year 2001 engine was capable of producing a higher output power than the model year 1997 version of the engine, 350 HP for the 2001 model compared to 305 HP for the 1997 model. Otherwise the technology level of the two engines appears to be comparable.

The applicable Tier 1 emission standards and emissions for the 2001 Cummins 6CTA8.3-M are shown in Table 2. The 2001 Cummins engine is well below the Tier 1 emissions standards in all four categories or criteria pollutant, coming the closest to the limit in NO_X emissions where the emission value of 5.19 g/bHP-h is 75% of the regulated value. For unburned hydrocarbon, carbon monoxide, and particulate matter emissions, the Cummins engine emits less than one-third of the permitted levels

Table 2. Tier 1 emission standards and emissions from the Cummins 2001 6CTA8.3 M engine.

	NO_X	HC	CO	PM
Tier 1 Emissions (g/bHP-h)	6.9	1.0	8.5	0.4
Cummins 2001 6CTA8.3 M emissions (g/bHP-h)	5.19	0.32	0.33	0.13

The engine emissions test cycle applicable to Tier 1 marine diesel engines between 5 and 30 liters in displacement is the ISO 8178 test cycle E3. This test cycle is compared to BUSL duty cycle in Table 3. The most notable difference is that the ISO 8178 E3 test cycle does not include an idle operating point whereas the BUSL spends 80-85% of its time under idling conditions. The operating condition with the highest weighting factor (mode 2, 75% power) is the operating condition representative of a cruising condition on the BUSL, and the condition under which the majority of the BUSL fuel is burned. Implications of the BUSL duty cycle are discussed in a later section.

Table 3. ISO 8178 engine test cycle and BUSL normal operating cycle.

ISO 8178 E3 test cycle	Mode 1	Mode 2	Mode 3	Mode 4
Power, %	100	75	50	25
Speed, %	100	91	80	63
Weighing Factor	0.2	0.5	0.15	0.15
BUSL duty cycle				
Power	Idle	Cruise	Full power	
Time (%)	80-85%	13-18%	2%	

Literature Survey of Emissions Changes with Biodiesel and Impact on BUSL

In order to bound the scope of the literature reviewed for this analysis, there was a focus on heavy duty engines of a similar era and technology level. The BUSL propulsion engines are equipped with turbochargers, inline mechanical fuel pumps, and direct injection fueling. They are not equipped with the capabilities for external cooled exhaust gas recirculation (EGR), common rail fuel injectors, or an engine controller capable of changing injection pressure, the number of injections, or the timing of injection. These features of more modern diesel engines enable lower emission operation, but also introduce numerous calibration-specific differences that can affect emissions. Thus, engines with more modern technologies are intentionally excluded from this review and analysis.

Two of the most cited references that outline the effect of biodiesel on criteria emissions are a 1998 review study by Graboski and McCormick [6] and a 2002 report by the U.S. EPA [7]. These two references use largely the same data set and come to similar conclusions. The overall relationship between emissions from heavy duty highway engines and the biodiesel content of the fuel is shown in Figure 1.

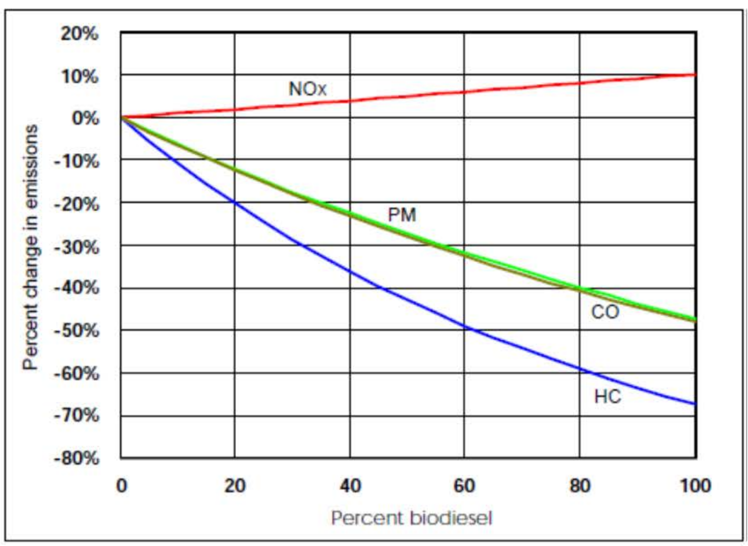


Figure 1. Average emission impacts of biodiesel for heavy duty diesel engines, taken from reference [7].

The data in Figure 1 is based on a variety of engines, ranging in model year from 1983 to 2001, as well as a variety of different vehicle driving cycles. The change in emissions as a function of biodiesel composition is highly variable, as is shown in Figure 2. Some of the studies also reported decreases in NO_X emissions at the 20, 50, and 100% biodiesel concentration levels. Nonetheless, the engines used to generate the Figure 1 are applicable to the BUSL because most

of them share many similar levels of engine technology (mechanical inline or rotary fuel injection, no EGR, no electronic engine controller).

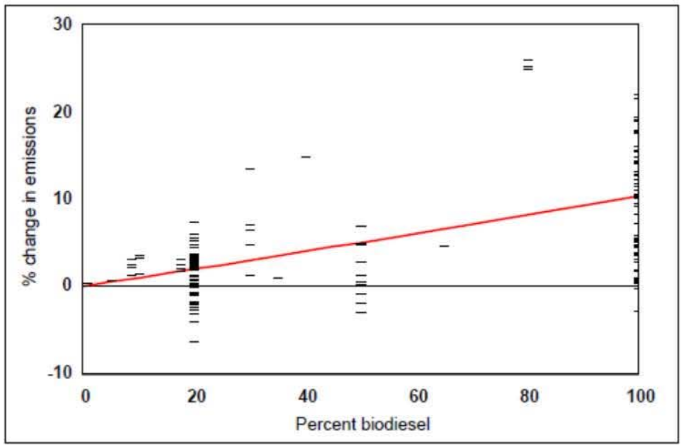


Figure 2. Comparison of individual NO_X data points to the NO_X emission correlation, taken from reference [7].

The emission trends from Figure 1 are applied to the 2001 Cummins engine and compared to baseline diesel emissions and Tier 1 regulations in Figure 3, with the same data in tabular format presented in Table 4. Error bars on the emissions predictions for biodiesel represent the minimum and maximum values observed in the data set used to make the correlation, as was shown in Figure 2. It can be seen that while the error bars are significant in some cases, the general trend of reductions in CO, HC, and PM hold, while NO_X emissions increase. It is noteworthy that even the largest percent increase in NO_X emissions observed in Figure 2 would still lead to emissions that are below the Tier 1 regulation.

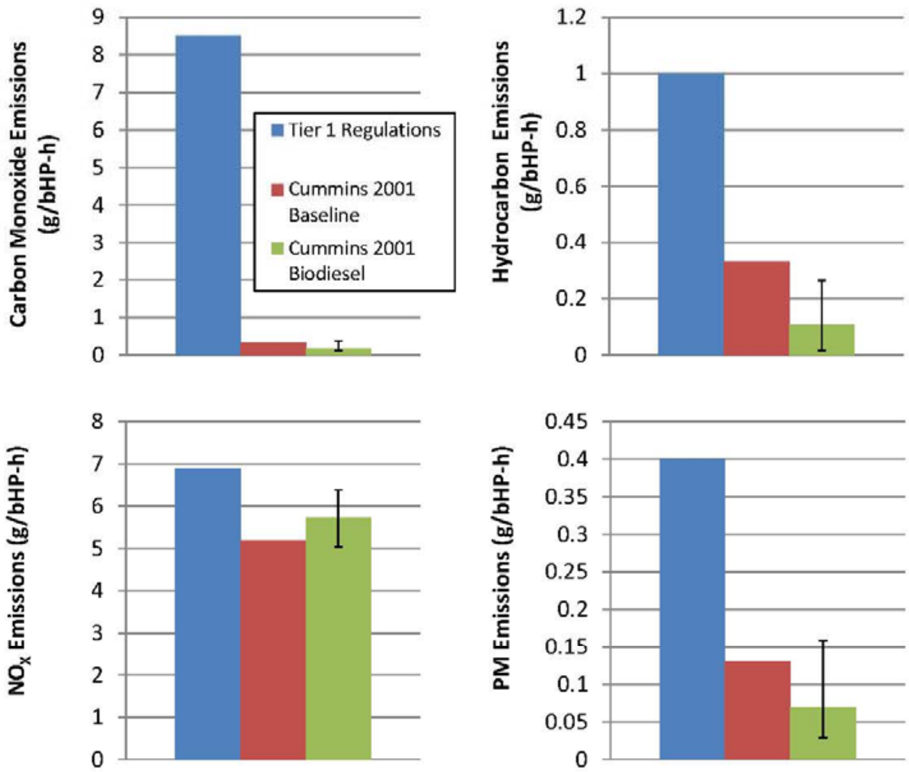


Figure 3. Predicted emissions for the 2001 Cummins 6CTA8.3-M engine with biodiesel compared to the baseline diesel and Tier 1 emissions. Predictions are based on the correlation in reference [7], and error bars represent the maximum and minimum values observed when producing the correlations.

Table 4. Tabular predicted emissions for the 2001 Cummins 6CTA8.3-M engine with biodiesel compared to the baseline diesel and Tier 1 emissions. Predictions are based on the correlation in reference [7].

	Tier 1 Standard	Cummins 2001 6CTA8.3-M (diesel)	Predicted Change with Biodiesel [7]	Cummins 2001 6CTA8.3-M (biodiesel)
CO (g/bHP-h)	8.5	0.32	-48.1%	0.17
HC (g/bHP-h)	1	0.33	-67.4%	0.11
NOX (g/bHP-h)	6.9	5.19	10.3%	5.72
PM (g/bHP-h)	0.4	0.13	-47.2%	0.07

BUSL Duty Cycle Considerations

One potential problem with the emissions predicted in Figure 3 is that the BUSL duty cycle differs substantially from the test cycles that the correlation in Figure 1 was built upon. The on-highway heavy duty cycles used either a Federal Test Procedure (FTP) composite cycle, FTP hot start cycle, or a standard 13-mode test for European emissions certification (regulation 49 (R49) test). The BUSL drive cycle is much narrower, spending the majority of its time at either cruise condition or at idle, as shown in Table 3. Additionally, in a marine engine, there is not as much variability in engine torque for a given engine speed because the submerged propeller in water has roughly a constant load for a given engine speed. The engine torque vs. speed for the 2001 version of the 6CTA8.3-M engine is shown in Figure 4, with the idle and cruise conditions for the BUSL superimposed. The engine torque vs. speed curve is taken from the Cummins Marine performance curve in Appendix A.

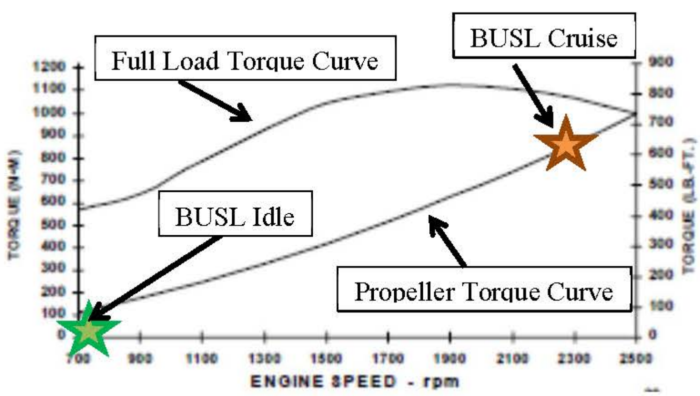


Figure 4. Engine torque vs. speed for full load and with the propeller for the 2001 version of the Cummins 6CTA8.3M engine, with approximate cruise (2300 rpm) and idle conditions superimposed.

The duty-cycle is important while considering emissions, as is the amount of fuel consumed at each operating condition. Table 5 shows the amount of fuel consumed at each of the BUSL operating conditions. The cruise and full power fuel consumption rates are for the baseline diesel fuel and taken from the Cummins marine performance curve in Appendix A for 2300 and 2500 rpm on the propeller torque curve. The idle fuel consumption rate is an estimate based on a previous ORNL emissions study from 15 idling trucks with idling speeds between 600 and 700 rpm. The idling fuel consumption of 0.65 gal/hr is consistent with the propeller torque curve fuel consumption of 0.9 gal/hr at 700 rpm with the propeller engaged, as shown in Appendix A.

Thus, Table 5 shows that while the engine is idled 80-85% of the time, this activity accounts for only 15-20% of the overall fuel consumption. Two-thirds to three-quarters of the fuel is consumed during cruise conditions, thus this is also where the majority of the emission formation takes place.

Table 5. BUSL duty cycle and approximate fuel consumption for baseline diesel fuel.

	Duty Cycle	Fuel Consumption (gal/hr)	% Fuel Consumed
Idle	80-85%	0.65	15-20%
Cruise	13-18%	14.1	67-74%
Full Power	2%	18.4	11-13%

Engine operating condition impacts the effect of biodiesel on engine emissions. Relevant results showing the dependence of engine operating condition on the impact of biodiesel on emissions can be found in reference [8] for relevant technology HD diesel engines. This report included results from a 9.6 L Volvo city bus engine and a 7.4 L Valmet tractor engine. Both engines are equipped with DI fueling and turbochargers, but there are some differences in the fuel pump technology (Volvo uses an inline pump whereas the Valmet uses a rotary pump).

These results from reference [8] are summarized in Figure 5 through Figure 8 for CO, HC, NO_X, and PM emissions as a percent change at specific locations on the engine map for a 30% blend of RME biodiesel. Also included on these are the approximate operating points for the idle and cruise conditions for the BUSL boat. It is worth noting that the Volvo and Valmet engines had different speed and torque limits than the Cummins engine. Thus, the approximate cruise conditions are based on a percent of the maximum speed and load.

At the BUSL cruise condition, there are consistent decreases in CO, unburned HC, and particulate matter emissions for both the Volvo and Valmet engines, although there is variability in the magnitude. NO_X emissions at the BUSL cruise condition show an increase for the Valmet engine, but any changes to the Volvo engine at this condition are small, and it is unclear whether it would result in an increase or decrease.

At the idle condition, biodiesel causes the Volvo emissions of HC and particulate matter to decrease, while there is no substantial change in either CO or NO_X emissions. For the Valmet engine, CO, HC, and NO_X emissions all decrease at the idle condition, but particulate emissions increase.

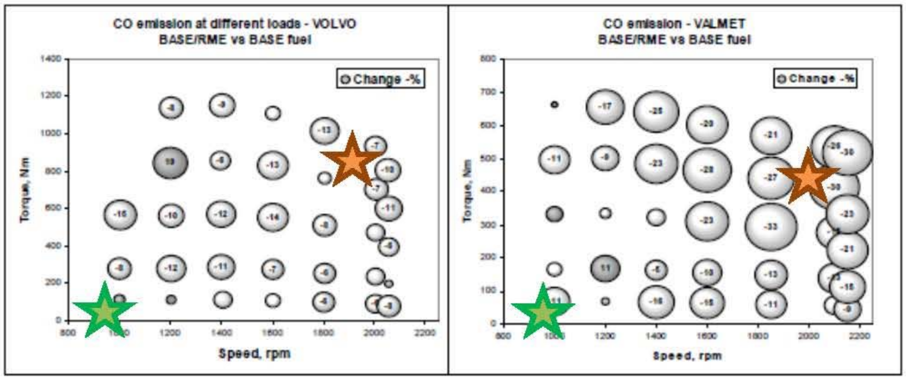


Figure 5. Relative differences (%) in CO emissions when a 30% RME blend is compared to the base fuel. Light bubbles mean lower emissions for the 30% RME blend. Orange stars represent the approximate BUSL cruise condition and green stars represent the approximate BUSL idle condition. Figure taken from reference [8].

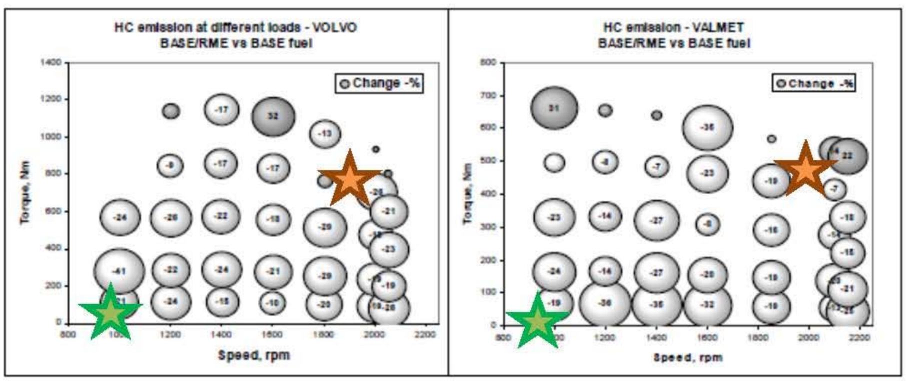


Figure 6. Relative differences (%) in unburned hydrocarbon emissions when a 30% RME blend is compared to the base fuel. Light bubbles mean lower emissions for the 30% RME blend. Orange stars represent the approximate BUSL cruise condition and green stars represent the approximate BUSL idle condition. Figure taken from reference [8].

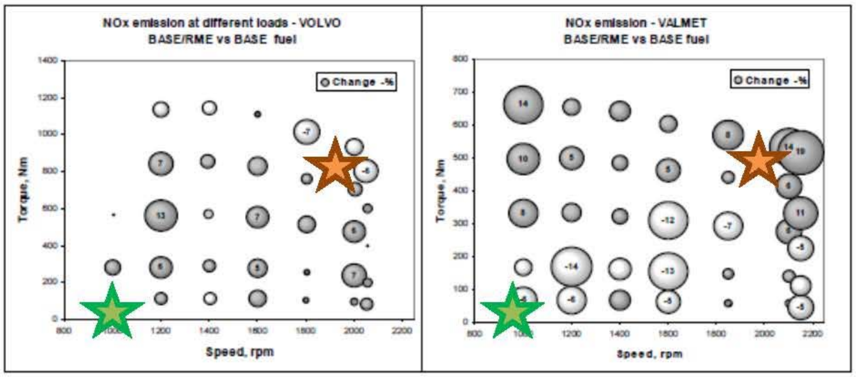


Figure 7. Relative differences (%) in NO_X emissions when a 30% RME blend is compared to the base fuel. Light bubbles mean lower emissions for the 30% RME blend. Orange stars represent the approximate BUSL cruise condition and green stars represent the approximate BUSL idle condition. Figure taken from reference [8].

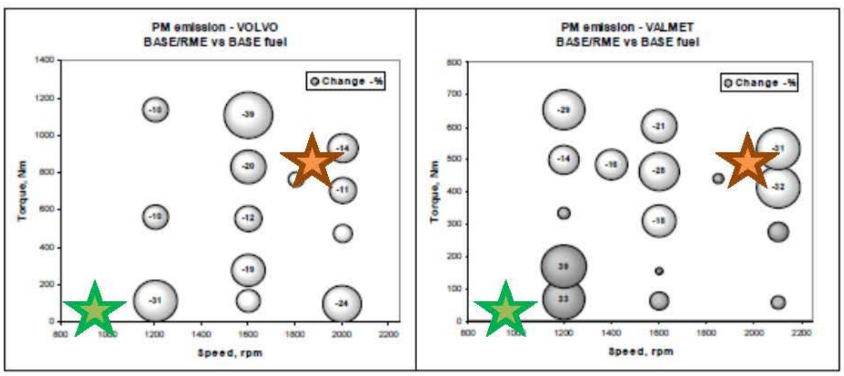


Figure 8. Relative differences (%) in particulate matter emissions when a 30% RME blend is compared to the base fuel. Light bubbles mean lower emissions for the 30% RME blend. Orange stars represent the approximate BUSL cruise condition and green stars represent the approximate BUSL idle condition. Figure taken from reference [8].

A related study used a 7.3 L Navistar engine with an electronically controlled fuel injection system to produce similar charts of relative emission differences between engine speed an load using 100% soy biodiesel [9]. Figure 9 shows that for this engine the relative NO_X emissions increase and the relative CO emissions decrease. It is noteworthy that the largest NO_X emissions increases for this engine occur under low-speed and high load conditions (i.e. 1000 rpm and 100% load). Because of the propeller torque curve on the BUSL, high load conditions are only seen at high engine speeds, conditions which have more modest increases in NO_X emissions. Thus, if the data in Figure 9 is representative of the BUSL, it is possible that the NO_X increase will be more modest than the NO_X increase in a vehicle with the same engine and same fuel. However, given the significant differences between the two engines in Figure 7 and the data in

Figure 9, there is insufficient data to conclude that the trend in Figure 9 is representative of the BUSL.

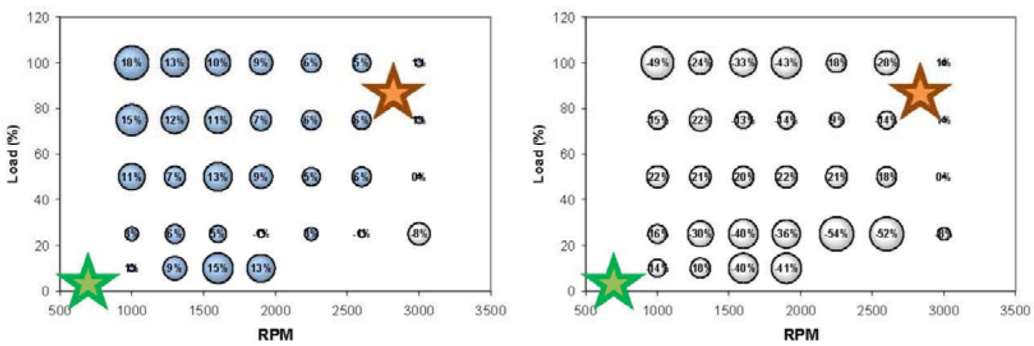


Figure 9. Relative differences in (a) percent NO_X emissions and (b) percent CO emissions when 100% soy biodiesel is compared to the base diesel fuel. Light bubbles mean lower emissions for the 100% soy biodiesel. Orange stars represent the approximate BUSL cruise condition and green stars represent the approximate BUSL idle condition. Figure taken from reference [9].

Emissions data showing the impacts of biodiesel across the engine map, as shown in Figure 5 through Figure 9Figure 8 is scarce open literature. The data are for only three engines, and it is clear that a significant amount of scatter exists in the emissions response with biodiesel, similar to the results shown in Figure 2. Thus, although the emission predictions shown in Figure 3 are built upon test cycles that differ substantially than the BUSL duty cycle, there is no information in the open literature that is specific enough to the BUSL engine/duty cycle combination to further refine the emission prediction.

Impact of Biodiesel on Greenhouse Gas Emissions

The Federal Energy Management Program's (FEMP) annual GHG and Sustainability Data Report [10] is a reporting workbook that can assist federal agencies in calculating and reporting their GHG emissions. The FEMP methodology offers no means of accounting for upstream GHG emissions from different feedstocks of alternative fuels in the data report. The Sustainability Data Report does record the biogenic emissions portion of biofuel combustion that are not currently counted under the regulatory requirements. The current FEMP reporting worksheet [8] focuses on tailpipe emissions for all fuels, but separates the biogenic CO_2 emissions from biofuel combustion and the anthropogenic CH_4 and N_2O emissions. The reasoning behind the separation is that the biomass is assumed to have decayed into CO_2 naturally but would not have resulted in the CH_4 and N_2O emissions that result when the fuels are combusted. There is possibility of accounting for upstream GHG emissions in the future, as

is currently done in the Renewable Fuel Standard (RFS2) ruling [11], and there is also some international precedence (EU Renewable Energy Directive (2009/28/EC [12])).

The following statements are from the EO 13514 GHG reporting guidance document:

> "Due to ongoing analysis, efforts to collect and synthesize data, and the development of accounting approaches that will appropriately reflect the true atmospheric impact of biogenic emissions, agencies are not required to include these emissions in their reduction targets under EO 13514 at this time, but agencies are required to inventory their biogenic GHG emissions." "Depending on the full emissions impact of biomass production and use, these emissions may or may not represent a net change in atmospheric carbon dioxide. This contrasts with carbon from fossil fuels, which was removed from the atmosphere millions of years ago." [2]

The immediate implication for the GHG accounting methodology used in the FEMP reporting tool is that there are no differences in the GHG emissions from biodiesel made from soybean or waste cooking oil. This is illustrated in Table 6 showing the FEMP reporting tool results for ULSD, B20 and B100 for 100 gasoline gallon equivalent (GGE) of fuel consumed. The small amount of CO_2e emissions produced with biodiesel are due to the small levels of CH_4 and N_2O emissions that are formed during the combustion process and would not have been produced during biomass decomposition to CO_2. The data is reported on the basis of 100 gallons because this is the average amount of fuel consumed by the BUSL in a single trip during normal operations [5]. The language in the current guidance document does not rule out future changes to account of lifecycle differences in biofuel feedstock production pathways.

Table 6. FEMP GHG Data Report Outputs for 100GGE of Fuel [8].

	ULSD	B20	B100
Biogenic CO_2e (kg)	0	184.6	923.0
Anthropogenic CO_2e (kg)	925.2	740.3	0.82
Total CO_2e (kg)	925.2	740.3	0.82

Impact of Waste Cooking Oil Biodiesel on Life-Cycle GHG Emissions

The net change in atmospheric GHGs for biodiesel made from any feedstock differs in the upstream emissions associated with the fuel production and distribution pathways. For the case of biodiesel from soybean oil as compared to biodiesel produced from waste cooking oil, the biggest differences in the fuel production pathway energy use and GHG emissions come from attribution of oilseed farming emissions being associated with the raw oil and not with the waste cooking oil which is considered a waste product (or residue). The lifecycle emissions can be separated in stages for the upstream emissions which are attributed to the fuel production and distribution and downstream which are attributed to the emissions from fuel combustion (tailpipe

emissions) as shown in Figure 10. This lifecycle is often described as a well-to-wheels pathway and compares the well-to-wheels pathways for conventional oilseed-based biodiesel and waste vegetable oil (WVO) biodiesel. The emissions attributed to fuel before it is burned are called the well-to-pump emissions and the downstream emissions are called the tank-to-wheels (or other means of propulsion).

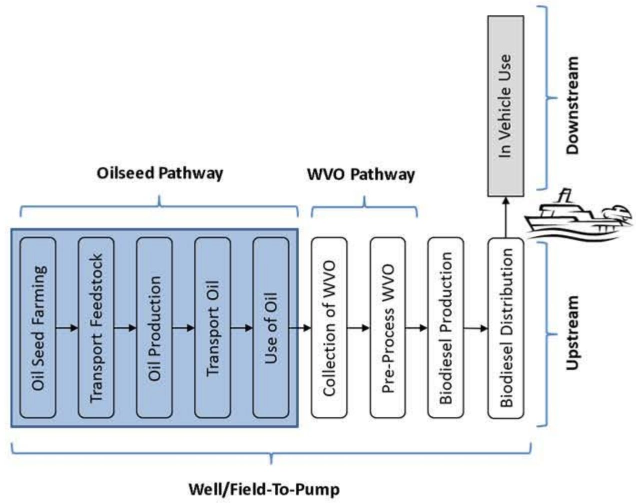


Figure 10. Lifecycle (or Well-to-Wheels) comparison of WVO and oilseed biodiesel.

Several approaches may be used to estimate the lifecycle GHG emissions with conventional fuels and biofuels which follow established lifecycle calculation methodologies [13]. Some of the publically available lifecycle analysis (LCA) tools are the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Model developed by Argonne National Laboratory for the US DOE [14], the BioGRACE tool which was devolped to calculated GHG emissions for the EU Renewable Energy Directive [15], and GHGenius developed by National Resources Canada [16]. A summary of publically and commercially available LCA tools can be found in the paper by Broch et. al. [13]. Where the LCA can differ (FEMP is still currently reviewing upstream emissions for EO 13514 accounting) is in the assumptions used for all of the steps involved in the upstream emissions calculations. Each approach makes assumptions for farming practices, the biodiesel production process, and transportation and distribution. The biggest differences between the different methodologies can be found in how the co-products are accounted for. In biodiesel production, the oil goes through a chemical process which results in a by-product of glycerin. The assumptions on the use of the glycerin can greatly affect the lifecycle emissions of the biodiesel fuel. If it assumed that the glycerin displaces current glycerin production, a credit is given to the LCA; however, if the glycerin is burned in a boiler onsite to generate heat, the emissions count against the lifecycle emissions.

There is already significant debate on both the energy return of biodiesel from various biodiesel feedstocks as well as lifecycle emissions calculations. A recent study compared over 40 biodiesel lifecycle studies and found of the 32 studies that showed energy return, the average value was 3.1 units of biodiesel produced for every 1.0 of energy consumed in its production [13]. The results were more spread for lifecycle GHG emissions with the over 40 studies showing an average reduction for biodiesel of 60% compared to petroleum diesel with a range of 10% to 90% reduction in lifecycle emissions [13]. The U.S. DOE reports that lifecycle GHG emissions from B100 could be more than 52% lower than from petroleum diesel [17].

A few studies have looked at the lifecycle emissions of waste cooking oil derived biodiesel, two of which [11,12] look at different scenarios on how the co-product attribution of emissions can affect the resultant lifecycle analysis. The studies showed a range of GHG savings for waste cooking oil derived biodiesel between 65.9 and 76.8% [18] and up to 85% [19], as compared to petroleum diesel fuel. The results of these two studies along with the results using the lifecycle tool known as BioGRACE which has a pathway for waste cooking oil built in [15], and GREET which was modified for waste cooking oil [14], are presented in Figure 11. Note that the lifecycle emissions are higher than the CO_2e emissions reported with the FEMP methodology, shown in Table 6, because the FEMP methodology does not include upstream CO_2e emissions. The columns represent the average lifecycle GHG CO_2e emissions using these different methodologies, while the error bars represent the minimum and maximum of the different studies. The results assume 100 gallons of diesel per BUSL trip and that B100 reduces fuel economy by 10% due to the lower energy content per gallon of B100 as compared to USLD. The error bars on the plots show the minimum and maximum results between the studies. The average results for the studies and lifecycle tools show a 46% reduction in lifecycle GHG with soy biodiesel and a 75% reduction with waste cooking oil biodiesel as compared to petroleum diesel. The data used to produce Figure 11 is shown in Figure 12 in terms of gCO_2e per unit of fuel energy (MJ) showing both the upstream and downstream components and net lifecycle (well-to-wheel) emissions.

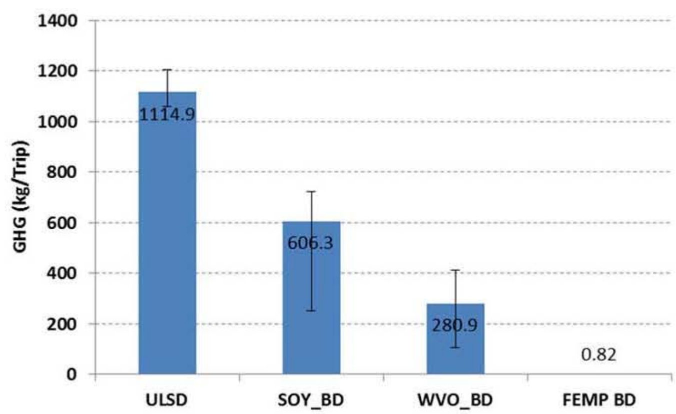


Figure 11. Lifecycle GHG emissions per BUSL trip for soy and WVO biodiesel compared to ULSD using published values (FEMP default biodiesel GHG emissions also shown).

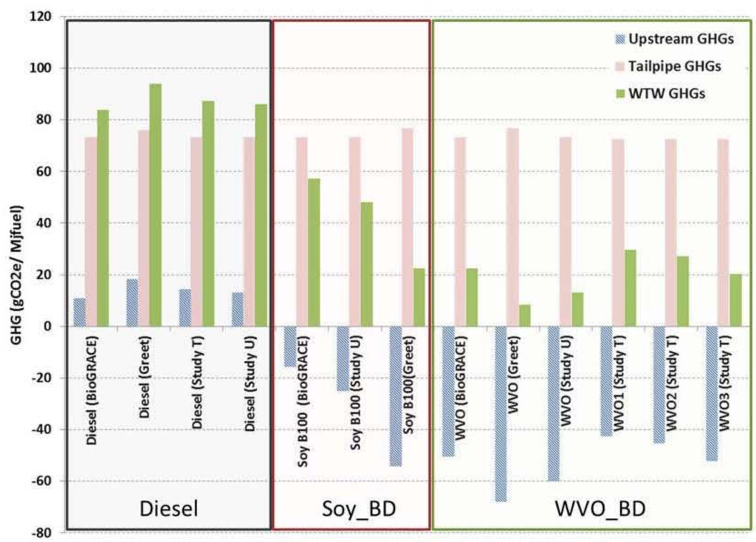


Figure 12. Lifecycle GHG emissions per MJ of fuel energy for all studies including upstream and downstream components.

Conclusions

This report provides a literature-based assessment of the impact of switching the fuel for the 49' BUSL boat from conventional petroleum-derived diesel fuel to 100% waste cooking oil biodiesel on the emissions of CO, HC, particulate matter, NO_X, and GHG. On average, there is a 48.1% reduction in CO, 67.4% reduction in HC, a 47.2% reduction in PM, and a 10.3% increase in NO_X emissions on a mass basis for a given amount of power delivered from the engine. We also found that the emissions response of an individual engine to biodiesel may vary considerably about a mean value.

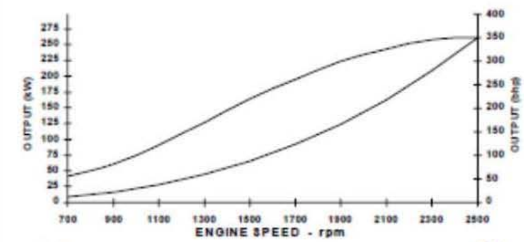
Switching from petroleum-derived diesel to biodiesel will reduce GHG emissions from 925.2 kg CO_2e to 0.82 kg CO_2e using the current FEMP reporting methodology. The use of B100 therefore produces nearly a 100% reduction in the reportable anthropogenic CO_2e emissions from BUSL propulsion. At present, there is no methodology within the FEMP calculation system to account for a difference in emissions based on biodiesel source material (e.g. waste cooking oil vs. virgin soy oil). If the FEMP system changes in the future to a system that uses a lifecycle analysis, the waste cooking oil will have an advantage over the soy biodiesel because emissions accumulated during farming and fuel production will not have to be accounted for. Recent lifecycle estimates showed a range of GHG savings for waste cooking oil derived biodiesel between 65.9 and 76.8% [18] and up to 85% as compared to petroleum diesel fuel. The extent of any advantage for waste cooking oil on a lifecycle analysis basis is highly dependent on the details of the reporting methodology.

Appendix A: Cummins 2001 6CTA8.3-M Performance and Emissions Data

CUMMINS ENGINE COMPANY, INC Columbus, Indiana 47201 Marine Performance Curve	Basic Engine Model: 6CTA8.3-M (SW)		Curve Number: M-90216	Marine Pg. No. 6C 59
	Engine Configuration: D413030MX02	CPL Code: 8089	Date: 28Aug04	

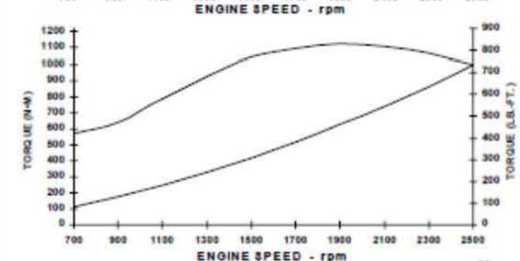
Displacement:	8.3 liters	[504.5 in.^{3}]		kW [bhp] @ rpm
Bore:	114 mm	[4.49 in.]	Advertised Power:	261 (350) @ 2500
Stroke:	135 mm	[5.32 in.]		
Fuel System:	Inline Bosch P7100		Aspiration:	Turbocharged/Sea Water Aftercooled
Cylinders:	6		Rating Type:	Intermittent

CERTIFIED: This marine diesel engine conforms with the NOx requirements of the International Maritime Organization (IMO), MARPOL 73/78 Annex VI, Regulation 13 as applicable.



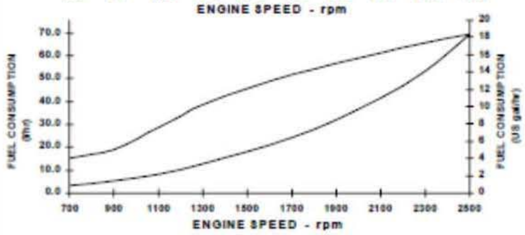
RATED POWER OUTPUT CURVE

rpm	kW	bhp
2500	261	350
2300	258	346
2100	244	327
1900	224	300
1700	195	262
1500	164	220
1300	126	169
1100	91	121
900	61	81
700	42	56



FULL LOAD TORQUE CURVE

rpm	Nm	lb.-ft.
2500	997	735
2300	1070	789
2100	1108	817
1900	1125	830
1700	1097	809
1500	1043	769
1300	926	683
1100	785	579
900	641	473
700	568	419



FUEL CONSUMPTION - PROP CURVE

rpm	l/hr	gal/hr
2500	69.7	18.4
2300	53.5	14.1
2100	41.6	11.0
1900	32.2	8.5
1700	24.4	6.5
1500	18.0	4.8
1300	12.8	3.4
1100	8.3	2.2
900	5.4	1.4
700	3.4	0.9

Rating Conditions: Ratings are based upon ISO 8665 and SAE J1228 reference conditions; air pressure of 100 kPa [29.612 in. Hg], air temperature 25°C [77°F], and 30% relative humidity. Power is rated in accordance with IMCI procedures. Member NMMA.

Rated Curves (upper) represent rated power at the crankshaft for mature gross engine performance capabilities obtained and corrected in accordance with ISO 3046. Propeller Curve (lower) is based on a typical fixed propeller demand curve using a 2.7 exponent. Propeller Shaft Power is approximately 3% less than rated crankshaft power after typical reverse/reduction gear losses and may vary depending on the type of gear or propulsion system used.

Fuel Consumption is based on fuel of 35° API gravity at 16°C [60°F] having LHV of 42,780 kj/kg [18390 Btu/lb] and weighing 838.9 g/liter [7.001 lb/U.S. gal].

Intermittent Rating: This power rating is intended for intermittent use in variable load application where full power is limited to two (2) hours out of every eight (8) hours of operation. Also, reduced power operation must be at or below 200 RPM of the maximum rated RPM. This rating is an ISO 3046 fuel stop power rating and is for applications that operate less than 1500 hours per year.

CHIEF ENGINEER

Marine
Pg. No.
6C
60

Marine Engine Performance Data

Curve No. M-90216
DS-4961
CPL: 8089
DATE: 28Aug04

General Engine Data

Engine Model		6CTA8.3-M (SW)
Rating Type		Intermittent
Rated Engine Power	kW [hp]	261 [350]
Rated Engine Speed	rpm	2500
Rated HP Production Tolerance	**%**	**±5**
Rated Engine Torque	Nm [ft/lb]	997 [735]
Peak Engine Torque @ 1900 RPM	**Nm [ft/lb]**	**1125 [830]**
Brake Mean Effective Pressure	kPa [PSI]	1515 [220]
Minimum Idle Speed Setting	rpm	600
Normal Idle Speed Variation	**rpm**	**±50**
High Idle Speed Range - Minimum	rpm	2750
High Idle Speed Range - Maximum	rpm	2850
Maximum Torque Capacity from Front of Crank[2]	**Nm [ft/lb]**	**N.A.**
Compression Ratio		15.35:1
Piston Speed	m/sec [ft/min]	**11.3 [2217]**
Firing Order		1-5-3-6-2-4
Weight (Dry) Engine Only - Average	**kg [lb]**	801 [1765]
Weight (Dry) Engine With Heat Exchanger System - Average	kg [lb]	855 [1885]

Fuel System[1]

Approximate Fuel Flow to Pump	liter/hr [gph]	193 [51]
Maximum Allowable Fuel Supply to Pump Temperature	**°C [°F]**	**60 [140]**
Approximate Fuel Flow Return to Tank	**liter/hr [gph]**	**123 [33]**
Approximate Fuel Return to Tank Temperature	**°C [°F]**	**N.A.**
Maximum Heat Rejection to Drain Fuel[5]	**kW [BTU/min]**	**N.A.**
Fuel Transfer Pump Pressure Range	Pa [PSI]	124 - 172 [18-25]

Air System[1]

Intake Manifold Pressure	mm Hg [in. Hg]	1219 [48]
Intake Air Flow	liter/sec [CFM]	369 [782]
Heat Rejection to Ambient	kW [BTU/min]	35 [2012]

Exhaust System[1]

Exhaust Gas Flow	liter/sec [CFM]	**779** [1650]
Exhaust Gas Temperature **(Turbine Out)**	°C [°F]	410 [770]
Exhaust Gas Temperature **(Manifold)**	°C [°F]	N.A.

Emissions (in accordance with ISO8178 Cycle E3)

NOx (Oxides of Nitrogen)	**g/kw-hr [g/bhp-hr]**	**6.96 [5.19]**
HC (Hydrocarbons)	**g/kw-hr [g/bhp-hr]**	**0.43 [0.32]**
CO (Carbon Monoxide)	**g/kw-hr [g/bhp-hr]**	**0.44 [0.33]**
PM (Particulate Matter)	**g/kw-hr [g/bhp-hr]**	**0.17 [0.13]**

Cooling System[1]

Coolant Flow to Engine Heat Exchanger/Keel Cooler	**liter/min [gpm]**	**284 [75]**
Standard Thermostat Operating Range (Min.)	**°C [°F]**	**71 [160]**
Standard Thermostat Operating Range (Max.)	**°C [°F]**	**83 [182]**
Heat Rejection to Engine Coolant[3]	kW [BTU/min]	257 [14,600]
Sea Water Flow **(With Heat Exchanger Option)[4]**	liter/min [gpm]	238 [63]
Pressure Cap Rating **(With Heat Exchanger Option)**	kPa [PSI]	103 [15]

INSTALLATION DRAWING

Engine Only		3170262

TBD = To Be Decided **N/A = Not Applicable** **N.A. = Not Available**

[1]All Data at Rated Conditions
[2]Consult Installation Direction Booklet for Limitations
[3]Heat rejection values are based on 50% water/ 50% ethylene glycol mix and do NOT include fouling factors. If sourcing your own cooler, a service fouling factor should be applied according to the cooler manufacturer's recommendation.
[4]Consult option notes for flow specifications of optional Cummins seawater pumps, if applicable.
[5]May not be at rated load and speed. Maximum heat rejection may occur at other than rated conditions.

CUMMINS ENGINE COMPANY, INC.
COLUMBUS, INDIANA

All Data is Subject to Change Without Notice - consult the following Cummins Intranet site for most recent data:
http://www.cummins.com

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APPENDIX C BIODIESEL TEST PLAN

The Biodiesel Test Plan is provided separately.

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APPENDIX D B100 FIELD TESTING GUIDE

Background:

Cummins, Inc. is supporting a field test of a BUSL boat of the US Coast Guard (USCG) which is being led by the USCG Research and Development Center (RDC). A 49-foot Buoy Utility Stern Loading (BUSL) boat from the USCG fleet at New Haven, Connecticut would be used for the field test. The signed CRADA between Cummins, Inc. and USCG RDC implies that there will be no exchange of money involved; however, Cummins would provide in-kind support to the project. This includes employee time and specific replacement parts on the engines being tested.

The deliverables for Cummins, Inc. include identifying the materials on the engines that are not compatible with B100, finding replacement parts, reviewing the test plan, reviewing the fuel system parts on the boat, etc.

Primary contacts:

- William Remley at Alion
- Chris Turner, Rich Hansen and Michael Coleman at USCG RDC

The boat has two C8.3 engines used for propulsion and one B3.9 engine as part of a genset unit. The engines to be used for this testing have the following serial numbers:

- C8.3: 45525043 and 45511870
- B3.9: 45451326

The field test involves running the boat with B100 for a period of more than 12 months. The testing is scheduled to commence in August 2012. The testing would continue through the Fall, Winter, Spring and Summer till August 2013, with occasional runs with diesel fuel. The USCG RDC has identified a fuel supplier for the testing.

Replacement parts:

Since these engines were manufactured in the 1996-97 time frame, there are several materials present on the engines which are not compatible with biodiesel. Hence, it is necessary to change these parts with new replacement parts which are compatible with biodiesel.

A detailed look was taken at the bill of materials of the fuel system on the engine and all fuel-wetted parts which are not compatible with biodiesel were identified. Replacement parts were then identified for these, based on the dimensions and the availability of the replacement part.

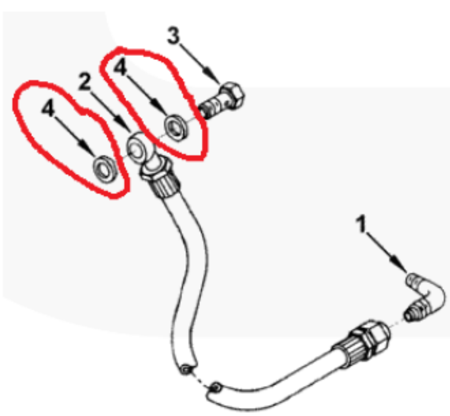
The following table summarizes the list of parts that need to be changed on the engines:

Engine	Part Number	Description	Material	Option used on	Quantity used per engine	Replacement Part
C8.3	3918190	Washer, Sealing	Rubber coated steel	FX9008 - Injection Pump Supply	2	3684342
C8.3	3903380	Seal, Banjo Connector	55002 - 99% Copper	FT9873-04 - Fuel Plumbing	6	3069182
C8.3	3918188	Washer, Sealing	Rubber coated steel	FT9873-04 - Fuel Plumbing	2	3069182
C8.3	3918192	Washer, Sealing	Rubber coated steel	FT9873-04 - Fuel Plumbing	2	3963988
C8.3	3918191	Washer, Sealing	Rubber coated steel	FS9006-03 - Fuel System Accessories	2	3963990
B3.9	3903380	Seal, Banjo Connector	Copper (99% min)	FT9901-02 - Fuel Plumbing	6	3069182
B3.9	3918188	Washer, Sealing	Rubber coated steel	FT9901-02 - Fuel Plumbing	2	3069182
B3.9	3918191	Washer, Sealing	Rubber coated steel	FS9088 - Fuel System Accessories	2	3963990
B3.9	3923083	Hose, Flexible	1/4" rubber tube, Single	FP97333 - Bosch Injection Pump	1	3923083M
B3.9	3918192	Washer, Sealing	Rubber coated steel	FF9741-04 - Fuel Filter Plumbing	2	3963988
B3.9	3918191	Washer, Sealing	Rubber coated Steel	FF9028-03 - Fuel Filter	2	3963990

Pictures of the assembly where these replacement parts are used are as below:

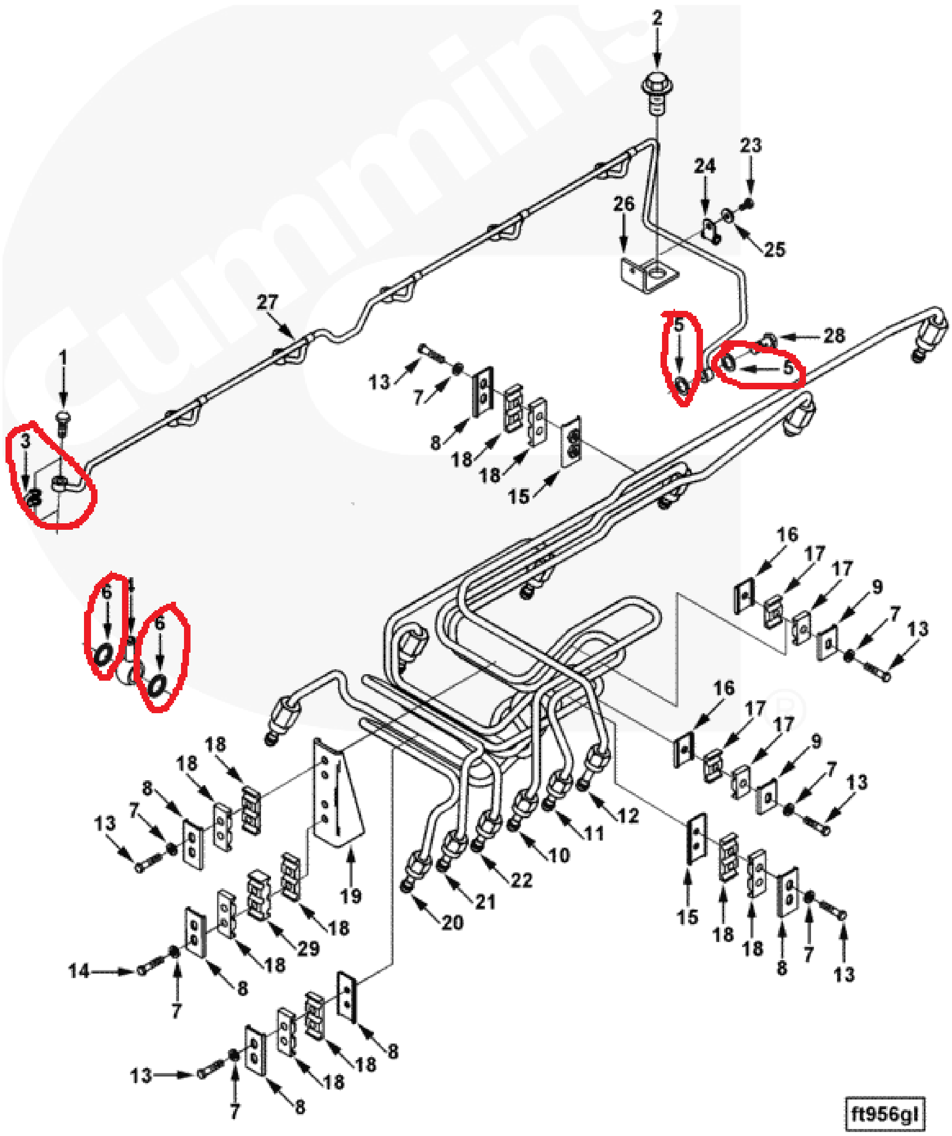
C8.3 Engine:

- **FX9008 – Injection Pump Supply:**



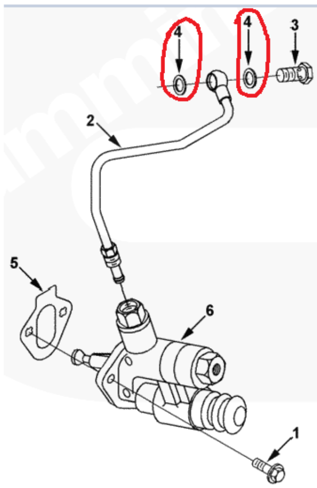
Current Part on the engine	Quantity	Part Number in above picture	Replacement Part
3918190	2	4	3684342

- **FT9873-04 – Fuel Plumbing:**



Current Part on the engine	Quantity	Part Number in above picture	Replacement Part
3903380	6	3	3069182
3918188	2	5	3069182
3918192	2	6	3963988

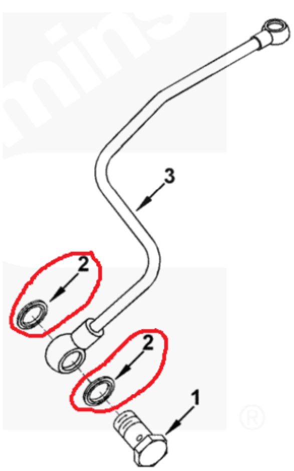
- **FS9006-03 – Fuel System Accessories:**



Current Part on the engine	Quantity	Part Number in above picture	Replacement Part
3918191	2	4	3963990

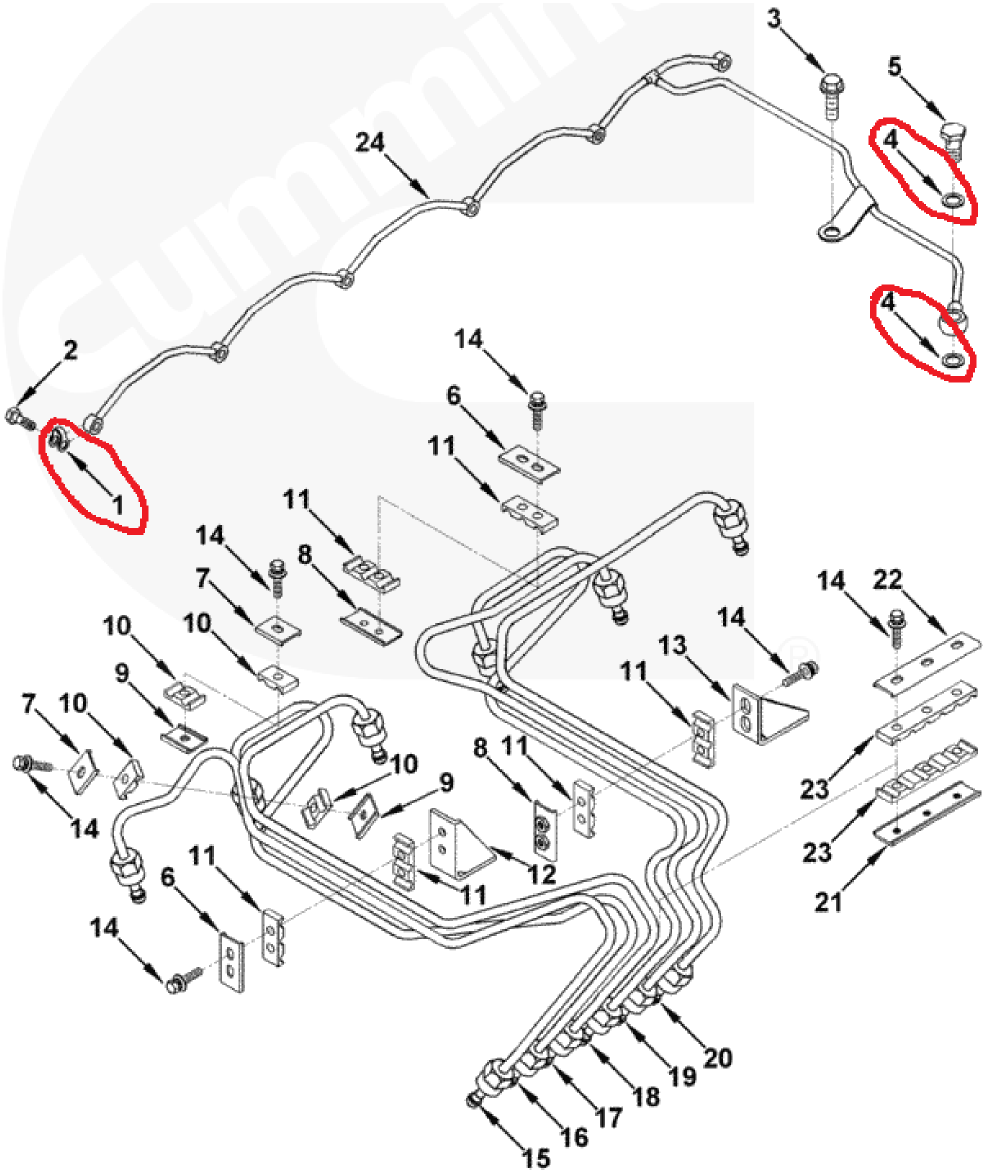
B3.9 Engine:

- **FF9741-04 – Fuel Filter Plumbing:**



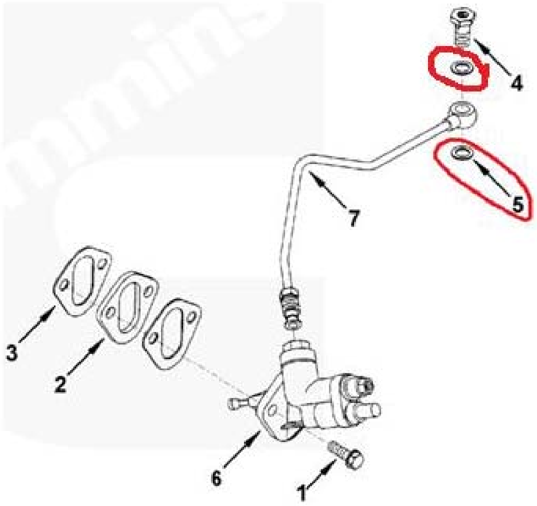
Current Part on the engine	Quantity	Part Number in above picture	Replacement Part
3918192	2	2	3963988

- **FT9901-02 – Fuel Plumbing:**



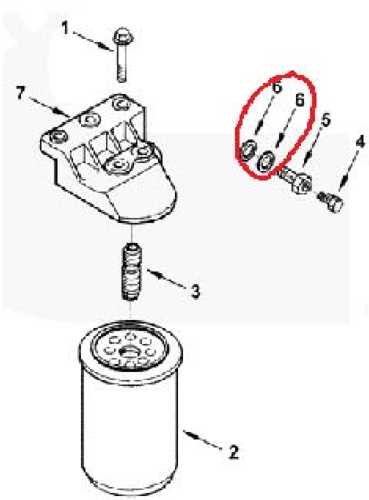
Current Part on the engine	Quantity	Part Number in above picture	Replacement Part
3903380	6	1	3069182
3918188	2	4	3069182

- **FS9088 – Fuel System Accessories:**



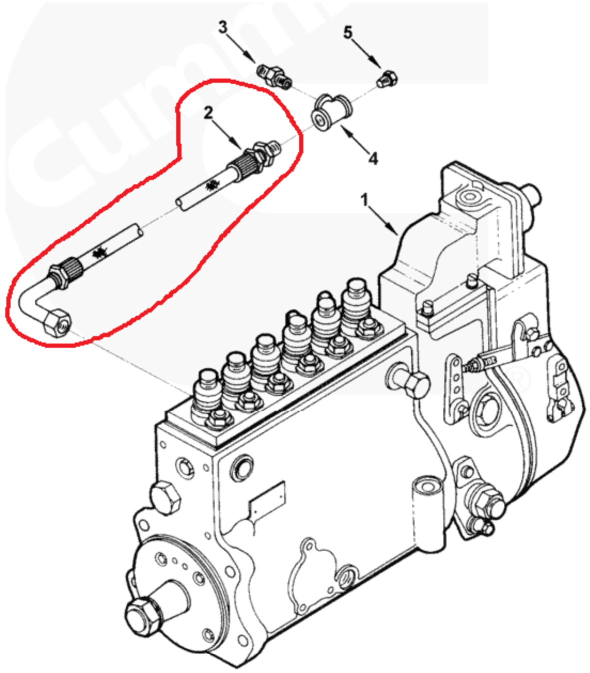
Current Part on the engine	Quantity	Part Number in above picture	Replacement Part
3918191	2	5	3963990

- **FF9028-03 – Fuel Filter:**



Current Part on the engine	Quantity	Part Number in above picture	Replacement Part
3918191	2	6	3963990

- **FP97333 – Bosch Injection Pump:**



Current Part on the engine	Quantity	Part Number in above picture	Replacement Part
3923083	1	2	3923083M

Procedures for installing the replacement parts would be similar to installing existing parts, as noted in the Service Manual for the respective engines. The Service Manual for these engines can be acquired from any Cummins distributor and is also available at quickserve.cummins.com.

General recommendations for the field test for using B100:

- Monitor water content in the tanks.
- Do not allow fuel to remain in vehicle fuel tank for extended shut down periods.
- Regularly check fuel system components for leaks
- Monitor fuel filter plugging regularly.
- Avoid all contact of biodiesel fuel with wiring harnesses and electrical connectors. The wiring harness and weather packing material will swell very quickly.
- Maintain appropriate fuel filter changes due to fuel filter gaskets will only last the fuel filter change interval.
- Do not store biodiesel fuel in direct sunlight.
- Adding antioxidants will help to increase fuel stability.

Oil sampling:

1. Collect oil samples from clean oil before it is filled into the engines.
2. Collect oil samples, if possible, every 50 hours of engine hours from start of test.
3. Collect an oil sample before any fuel change (from diesel to biodiesel and vice versa) is done on the boats.
4. Start on the conservative side with oil drain intervals (reduce them by half from what is currently practiced). Once the results from oil sampling are obtained, the intervals need to be determined accordingly.
5. Submit the oil samples as soon as they are collected so one can track the numbers as they report the results.
6. When the samples are submitted, request that the samples get tested for Fuel Dilution (biodiesel and diesel). Some labs may not test for both biodiesel and diesel in the engine oil, so it is important that the lab is aware of these expectations.
7. Also, request for the regular routine analysis on the samples to make sure the other properties are still within normal range (viscosity, soot. TBN, wear metals, and additive metals).
8. Collect fuel samples so a baseline of the biodiesel can also be documented.

Refer the "Fuels for Cummins Engines" Service Bulletin from Cummins, Inc. for general recommendations for running engines with B20 fuel. The Service Bulletin is available from any Cummins distributor and is also available at quickserve.cummins.com.

For any questions, please contact Harsh Khandelwal from Cummins, Inc. at 812-377-1918 or harsh.khandelwal@cummins.com.